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THE PALEOECOLOGICAL HISTORY OF TWO PENNSYLVANIAN BLACK SHALES

RAINER ZANGERL

AND

EUGENE S. RICHARDSON, JR.

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With Contributions by

Bertram G. Woodland, Robert L. Miller, Richard C. Neavel,
and Harry A. Tourtelot

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THE PALEOECOLOGICAL HISTORY
OF TWO PENNSYLVANIAN BLACK SHALES

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THE PALEOECOLOGICAL HISTORY OF TWO PENNSYLVANIAN BLACK SHALES

I. FOREWORD

A study requiring as much effort in the physical gathering of the raw data as has this one, depends on the assistance of a number of people. A succession of students from Antioch College, who were working at the Museum under their co-operative study program, helped us in the field and in the laboratory on the laborious task of charting the fossil content of the Mecca Quarry: Shirley Hale, Robin Rothman, Jane Black, Janet Bowman, Cynthia Belton, Barbara Best, Margot Marple, Patricia Hutson, John Nash, Sally Higginbotham, Duncan Dunlap, and notably Peter Garrison, who chose to return to this project for four work periods and was an outstandingly competent assistant in the field and in the laboratory.

We greatly appreciate the help of the following persons, who volunteered their services: Gale Zelnick, David Goldberger, Richard McClung, Kenneth Jones, Leon Rainers, William Herbert, the late Shimon Angress from Hebrew University in Israel, Charles Knowles, Chin Chen, John L. McLuckie, Cameron Gifford, and Edward and Philip Huneke.

Steven Collings of Rockville, Indiana, has been our most indefatigable field assistant. Assistants employed under a National Science Foundation grant were Robert Angel, Dr. Julian Sestini, now Professor of Geology at the University of Bahía, Brazil, and Jay Wollin.

A number of residents of Parke County, Indiana, took a friendly interest in our work. We wish to express our thanks to Mr. and Mrs. Paul B. Collings, Mr. and Mrs. Jack B. Snowden, Mr. Warren Buchanan, and Mr. Frank Haworth, all of Rockville, for their many courtesies and for their hospitality. Mr. and Mrs. Kenneth Cloyd, Mr. and Mrs. P. H. Logan, Mr. and Mrs. Lawrence Smith, Mr. and Mrs. Milton Davies, and Mr. Noble Auld permitted us to camp on their land, thus greatly facilitating the field work.

We are most grateful, indeed, to Mr. Logan and Mr. Auld, who generously permitted us to establish on their land the two quarries (Logan and Mecca) that yielded the fundamental data for the present study. Mr. Gerald Garrard, operator of the Cayuga Brick and Tile Corporation pit near Bloomingdale, stripped the Logan Quarry of overburden and later, while opening up an extension to the clay pit, called our attention to an exposure of the Logan Quarry shale, which he cleared and preserved for us; this became the Garrard Quarry.

In the course of our field work we received valuable help in the form of field conferences from Dr. Charles E. Wier, Head of the Coal Section of the Indiana Geological Survey, and Dr. G. K. Guennel, Dr. S. A. Friedman and Mr. H. C. Hutchison, members of the Section.

Our field work in the bayou country of Louisiana was made possible by the generous co-operation of Dr. Fred R. Cagle, Dr. Donald Tinkle, Dr. Royal D. Suttkus, Dr. Joseph T. Ewen and Mr. "Fitz" Fitzjarrel, of the Department of Zoology, Tulane University.

We are grateful for having had the opportunity to discuss various aspects of the problem with Professors J. Marvin Weller, Everett C. Olson, Ralph Johnson, and J Harlan Bretz, of the University of Chicago. Dr. George DeVore, formerly of that university, kindly provided us with spectrographic analyses of the Mecca Quarry shale, as well as with his interpretations of the significance of the results.

We are further indebted to the following colleagues for the benefit of their experience or active assistance in the field: Dr. Harold Wanless, of the University of Illinois; Dr. Adolf Seilacher, of the University of Tübingen; Dr. Frank H. T. Rhodes, of the University College of Wales, Swansea; Dr. Richard J. Russell and Mr. Ed. Orton, of Louisiana State University; Dr. Archie McAlpin, of the University of Notre Dame; Dr. Heintz Lowenstam, of the California Institute of Technology; and Dr. Perry Gilbert, of Cornell University.

Colleagues on the Museum staff helped us in a variety of ways. Engaged in the excavation of the Museum's quarries at one time or another were Messrs. William D. Turnbull, Orville L. Gilpin, Ronald J. Lambert, Bruce Erickson, Edwards N. Richardson, and D. Dwight Davis. Mr. Davis also made some fine photographs. Mr. David Techter helped us curate the collection of fossils from these quarries, and Messrs. John Bayalis and Homer Holdren advised us on photographic matters. Mrs. Evelyn Shahroch with inexhaustible patience typed the seemingly endless drafts of the manuscript. The careful editorial attention of Miss Lillian Ross leaves us confident that the following paper expresses what we had intended to say.

To all of these persons go our sincere thanks. With gratitude, furthermore, we acknowledge financial support from the Maurice L. Richardson Paleontological Fund at Chicago Natural History Museum, The Geological Society of America (Grant No. 661–55), and the National Science Foundation (Grant No. G-7140).

The sympathetic encouragement and support of the Museum administration is gratefully acknowledged to Chairman Stanley Field, President Clifford C. Gregg, and Director E. Leland Webber.

II. INTRODUCTION

The following study endeavors to analyze the forces and factors, both physical and biological, that produced the conditions leading to the formation of black carbonaceous shale deposits of Pennsylvanian age that contain tremendous concentrations of skeletons of vertebrates in association with invertebrates. The results of the study are thus of interest not merely to the paleontologist but to the geologist as well.

Paleoecology—as we have come to understand it in recent years—and neoecology both investigate the complex relationships of organisms and environment, but the two sciences do not rest on the same erkenntnistheoretic plane and their results are thus comparable only to a limited extent. Most of the physical and biological characteristics of a modern environment may be determined (at least potentially) by *direct* observation and determination. Paleoecological insight, by contrast, is based on observations and determinations that provide (for the most part) *indirect* evidence only. Hence the reliability of the interpretations is not of the same order in the two sciences.

There is, furthermore, a difference in dimension between the two disciplines. Rarely, if ever, can a changing ecological system be studied adequately, because of the transient nature of many of the events, and of man as the observer. Time, on the other hand, is an important factor in paleoecological inquiry. The range of time, in most examples, however, far exceeds human experience; hence paleoecological changes are usually processes with time dimensions vastly different from those encountered in neoecology.

Where paleoecological inquiry concerns itself with the fate of an individual organism the time dimension may be of the same order of magnitude as in modern ecology. It was primarily Weigelt (1927) who pointed out the potential merit of this aspect of paleoecological insight, which he called biostratonomy. It emphasizes the importance of the positional relationships not only of organisms and sediment but also of fossils to one another as well as the significance of the factors and processes that act upon the organism until its final burial in the sediment. A comprehensive treatment of this aspect of paleoecology was given by Müller (1951; 1957). There are extremely rare examples where biostratonomic inquiry is favored by unusually striking evidence and where the time dimension is of an order well within human experience. The present study may serve as such an example.

Both the Mecca Quarry and Logan Quarry shales are deposits containing enormous concentrations of vertebrate skeletons. Such concentrations are extremely rare, because they depend upon the simultaneous action of at least three mechanisms: one for the concentration of the living (or recently dead) organisms, another for their destruction (a cause of death), and a third that insures rapid burial. Individually, these mechanisms are by no means unusual phenomena or rare occurrences; for example, mass mortality (often periodic) among marine fishes due to a variety of causes is well known in the Present (Brongersma-Sanders, 1957). Destruction of large numbers of individuals alone, however, does not guarantee potential fossil concentrations of articulated skeletons. In warm (20 to 30° C.), aerated water, bacterial destruction of the soft parts is an astonishingly rapid process, measurable in days or weeks rather than in months; even anaerobic decomposition under these conditions, though much slower, quickly leads to disarticulation. In cold water, bacterial decomposition is very slow, but the chances that carcasses will be preserved as fossil skeletons are little better than at higher temperatures, because in the absence of poisonous decay products, the bottom remains habitable by innumerable scavengers. In general, a relatively rapid rate of sedimentation appears to be a prime requisite for the preservation of intact skeletons, regardless of all the other physical attributes of the burial environment.

Since the preservation of intact vertebrate skeletons is ordinarily improbable except under rather narrowly definable environmental conditions, their presence in a deposit is of the utmost biostratonomic significance.

For practical reasons, we suspect, most biostratonomic studies concern themselves with but one aspect of the problem, rather than with the problem as a whole. Biostratonomic conclusions are based, for example, on analyses of the chemical or petrographic composition of a sediment, or its microscopic structure; on the qualitative or quantitative aspects of the fossil content; or on stratigraphic evidence. All such analyses are amenable to a variety of plausible interpretations. This dilemma was largely overcome in the present study by the investigation of every facet of the problem that lay within the realm of our competency. It soon became obvious that, while several reasonable interpretations were possible in any one of the areas of inquiry, most of them were in direct conflict with evidence elsewhere. It need scarcely be pointed out that, regardless of the volume of evidence at hand, we are never in possession of *all* of it. Hence, our overall conclusions presented in this paper are simply those that do not conflict with any of the evidence presently at hand.

In recent years the validity of the principle of uniformitarianism (or actualism) has been challenged, most recently by Krynine (1956): "Uniformitarianism is a dangerous doctrine." Unless we are to believe, as Krynine implies, that the catch phrase, "the present is the key to the past," has been taken to mean that all geological phenomena may be explained in terms of present-day conditions, Krynine's objections seem rather pointless. We doubt that the geologic profession at large entertains any such naive notions; no historic science, on the other hand, is immune to occasional carelessness with methodological procedures. Uniformitarianism, as we understand the principle, maintains that the fundamental laws of physics and biology were no different in the past from what they are today. We are thus not prepared to admit, for example, that the physical forces that produced erosion in Pennsylvanian time acted on a principle different from the one on which they act today; or that the germ plasm was not involved in genetic changes prior to the Jurassic; or that the molecular bonding of two atoms of hydrogen with one of oxygen produced a substance other than water during the Cretaceous. To question the perpetuity of these laws is tantamount to denying the validity of all historic inquiry.

The practical application of the principle of uniformitarianism to geological problems requires the comparison of phenomena of the past with apparently similar phenomena of the present. Methodologically acceptable procedure, however, demands that the limits of this comparability be clearly understood. The degree of comparability obviously may vary from case to case, but the *a priori* assumption that two phenomena widely spaced in time cannot be directly comparable is as erroneous as the blanket denial of the "vitiating effects" of diagenetic processes.

Biostratonomic work is vitally concerned with time as a dimension. The myriad processes that run their courses in a depositional environment require various intervals of time for their completion, and, moreover, progress at various rates of speed. For this reason it becomes necessary to view such evidence as they may have left behind in proper perspective; for example, a period of deposition of one year in Pennsylvanian time appears as an infinitesimally small interval if it is viewed against the time that has since elapsed. In terms of the life expectancy of a fish, however, it is a moderately long period; and in terms of rate of reproduction of bacteria it is enormously long. Moreover, confidence in biostratonomic interpretations increases sharply with our ability to relate a phenomenon of the past to the order of magnitude of absolute time involved in its genesis. An example from this study may illustrate this point. Mecca Quarry shale is twelve inches thick at the site of Mecca Quarry. It consists of eight alternating levels of black and gray sheety shale with a very dense concentration of vertebrate remains in the black levels. The biostratonomic meaning of this periodicity would differ with differing estimates of the time required for the deposition of the twelve inches of shale. The assumption of a few years would suggest yearly or seasonal cycles, one thousand years would probably indicate climatic cycles, and ten thousand years would imply a periodicity of an even higher order. In turn, all the subsidiary evidence would have to be explained in different terms under each assumption. While we have been able to determine the rate of deposition in the present example, our method is probably applicable only under the most favorable circumstances; its merits should be tested elsewhere, however.

The present study is a detailed account of the biostratonomy of two thin seams of black shale over an area of a few miles along their outcrop belts. In terms of the size of the Eastern Interior (Illinois) Basin, to which they belong, the area studied is little more than a point on the map. In terms of time, the two shales taken alone represent but a tiny fraction of the depositional history of the Illinois Basin. Yet these two black shales have furnished a wealth of evidence concerning the pattern of ecological conditions that prevailed in that area during repeated transgressions of an epicontinental sea across marginal coal swamps.

Since the specific environmental conditions prevailing at any given geographic point are influenced or even determined by forces operating over a much larger area, it is possible to arrive at valid generalizations concerning the latter. The changing physiographic character of the depositional environments of the Mecca and Logan Quarry shales, located as they were along the frayed fringes of the epicontinental sea, is a reflection of geologic events far beyond the limits of the observed area both in the higher hinterland and in the Illinois Basin. The specific ecological situations at Logan and Mecca Quarries, on the other hand, were local phenomena even within our small area of observation. Very likely, however, similar conditions existed from time to time, here and there, all around the ever-changing coastline of the shallow sea that filled the basin.

III. THE BIOSTRATONOMY OF THE MECCA AND LOGAN QUARRY SHALES

A. SCOPE AND OBJECTIVES OF THE PRESENT STUDY

It lies in the nature of the subject that a study of this kind cannot be planned at the outset. For one thing, it depends on the discovery of a particularly favorable deposit, rich in biostratonomic evidence. The discovery of such a deposit is a matter of good fortune because its merits can be judged only after much of the evidence has been gathered and analyzed. Because it is not possible to predict the nature of the evidence that might be uncovered, the approach to the problem cannot be delineated beforehand other than in vague terms, and the scope as well as the objectives of the investigation are bound to be expanded into unsuspected areas.

The deposit that prompted the present study was accidentally discovered by the senior author in the spring of 1950. A number of subsequent visits to the discovery site left little doubt that the deposit contained a vast concentration of marine vertebrate remains, many of them partially articulated. That this shale lay directly upon a seam of coal suggested an interesting paleoecological situation, while the unusual even-beddedness and ready splittability of the shale together with its limited overall thickness made it possible to obtain an unweathered, coherent sample of adequate dimensions.

The initial objectives were to determine the nature of the fossil content, its horizontal distribution within narrow zones, and its vertical distribution. For this purpose the Mecca Quarry was established near the discovery site in Parke County, Indiana (see map, fig. 1).

In the course of extracting information from the shale sample and thereby reducing it to rubble, we realized that the density of fossil concentration coincided with the relative blackness of the shale levels. Determination of the relative gray-tone values of the shale, level for level, was accomplished by two independent methods: The relative grayness was optically determined (see p. 16); the quantitative occurrence of the principal constituents of the shale was determined in thin sections ground vertical to the bedding. The thin sections revealed a number of significant features which led to an analysis of the principal components of the shale.

In the course of stratigraphic field work along the outcrop belt of the Mecca Quarry shale we discovered that vertebrate concentrations of notable density occur in at least three sheety black shale horizons below the Mecca Quarry shale. The detailed correlation of these beds was by no means firmly established in the literature. At one site a beautifully preserved large shark was discovered and excavated; the shale at that site, two cyclothems below the Mecca Quarry shale, seemed so promising that we decided to establish a second, much larger quarry (Logan Quarry, see map, fig. 1). This produced several hundred skeletons of essentially the same fauna (Mecca fauna) as that contained in the Mecca Quarry shale, but the specimens are better preserved and are of great importance in the interpretation of the depositional aspects of the fossils in the black shales. The microscopic structure of the Logan Quarry shale was compared with that of the Mecca Quarry shale (see p. 105).

In the course of renewed commercial stripping of overburden in a clay pit only half a mile from Logan Quarry, the Logan Quarry shale was horizontally exposed. This pro-

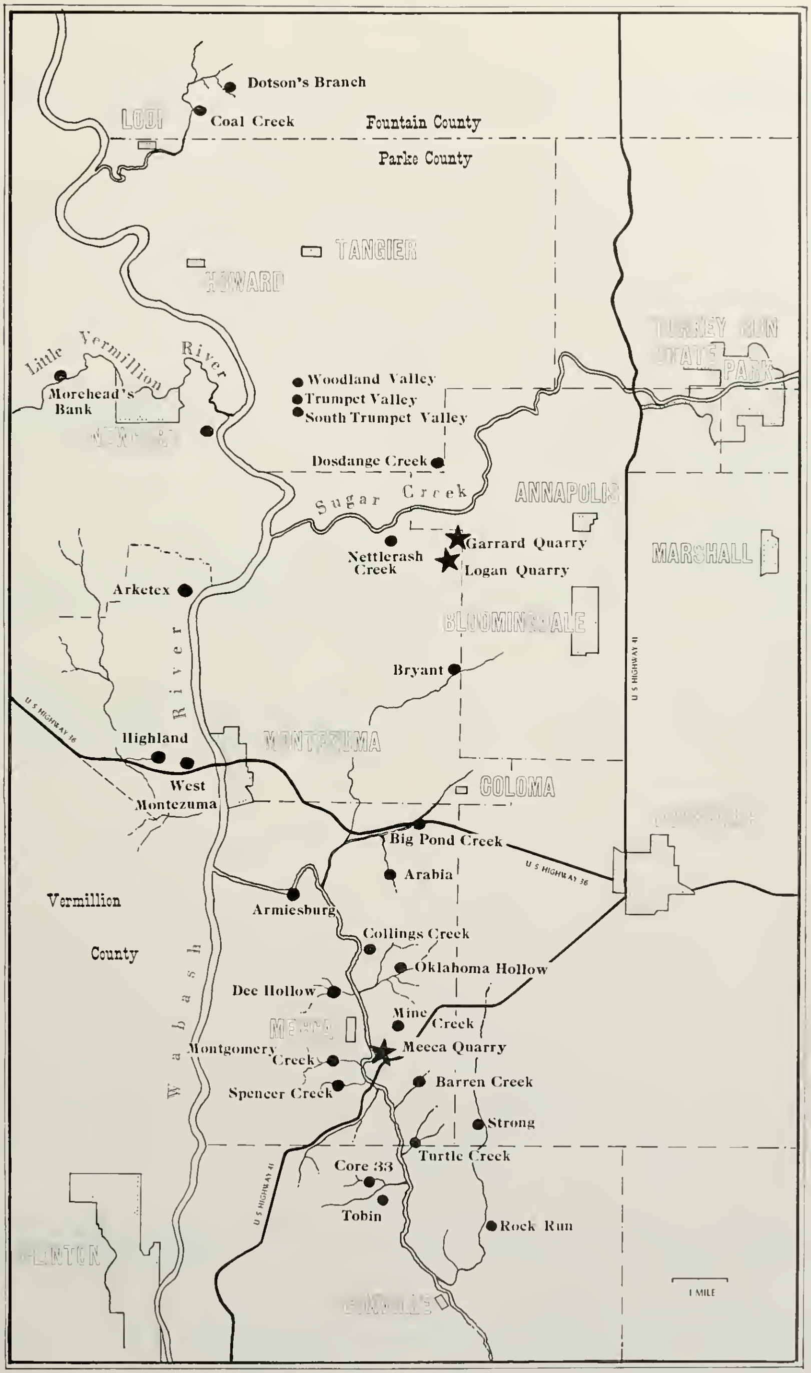
Dotson's Branch
Coal Creek
LODI
Fountain County
Parke County
TANGIER
HOWARD
TURKEY RUN STATE PARK
Little Vermillion River
Morehead's Bank
Woodland Valley
Trumpet Valley
South Trumpet Valley
Dosdange Creek
Sugar Creek
ANNAPOLIS
Garrard Quarry
Logan Quarry
Nettlerash Creek
MARSHALL
Arketex
River
BLOOMINGDALE
Bryant
U S HIGHWAY 41
U S HIGHWAY 36
Highland
West Montezuma
MONTEZUMA
COLOMA
Big Pond Creek
Arabia
Vermillion County
Armiesburg
Collings Creek
Oklahoma Hollow
Dee Hollow
Wabash
MECCA
Mine Creek
Montgomery Creek
Mecca Quarry
Spencer Creek
Barren Creek
Strong
Turtle Creek
Core 33
Tobin
Rock Run
CLINTON
1 MILE

FIG. 1. Map of parts of Parke, Vermillion and Fountain Counties, Indiana, showing localities cited in text.

vided a passing opportunity to quarry the shale with a minimum of effort. The major part of the section at this site (Garrard Quarry) proved to be a fresh-water deposit containing an entirely different fauna (humulite fauna).

Analysis of the fossil content at the three quarry sites in terms of its depositional character produced a wealth of fascinating biostratonomic evidence. It was possible, for example, to distinguish the effects of aerobic and anaerobic processes of bacterial decomposition in carcasses, regurgitated prey and coprolites. Since anaerobic decomposition followed the aerobic degradation it was possible to determine the thickness of sediment that accumulated on top of the carcasses during the aerobic phase of decomposition. These same features, furthermore, provided insight into the nature and degree of compaction of the sediment under study, and into the rate of its deposition.

The overall character of the Mecca and Logan Quarry shales suggested a rather unusual environment of deposition. Modern situations where black muds (consisting largely of particulate plant decomposition products) are forming occur here and there along the Gulf Coastal Plain of North America (and no doubt elsewhere). They are small ponds, lakes and bayous amid cypress swamps, often covered by a floating mat of vegetation (*flotant*). Field acquaintance with these situations seemed mandatory, not only to study the general environment and the character of the sediment, but also to conduct field experiments to determine speeds of bacterial decomposition of fishes at temperatures and under conditions at least similar to those that apparently prevailed at the sites of Mecca and Logan Quarries.

We made further analyses of the fossil content, inquiring into the causes of death of the animals and the fate of the carcasses. Of more directly biological interest are the relationships between the density of the burial community and that of the living population, as well as trophic relationships among the organisms of the Mecca and Logan Quarry environments.

B. TECHNIQUES OF INVESTIGATION

1. *MECCA QUARRY: FIELD METHODS*

The Mecca Quarry is located along the side of a small ravine (see map, fig. 10) about 500 feet north-northeast of the original discovery site of the Mecca Quarry shale, which is beside the Lyford to Rockville highway (U.S. Highway 41). The Pleistocene overburden and a thickness of several feet of Pennsylvanian drab shale containing several thin bands of limestone (Velpen limestone) were removed by bulldozer, down to a level approximately one foot above the even-bedded black shale. This was an unevenly bedded, dark gray shale that was removed with hand tools. The dimensions of the quarry surface were approximately 12 by 15 feet (fig. 3 and pls. 1 and 2). Along the outcrop the shale was weathered to a depth of about one foot except along the joints, where the effects of weathering extended deep into the quarry.

Very early in the course of quarrying the shale we noted that major and minor bedding planes could be distinguished, and this provided us with a natural level-designation system. Since the quarrying had to proceed from the top to the bottom, the alphabetical and numerical sequences are the reverse of the depositional sequence (see fig. 2).

We originally planned to peel off the even-bedded black shale and to chart the fossil content, level for level, in the field. This was not feasible, however, since the uncovered shale became warped severely by exposure to alternate rain and hot sun; furthermore,

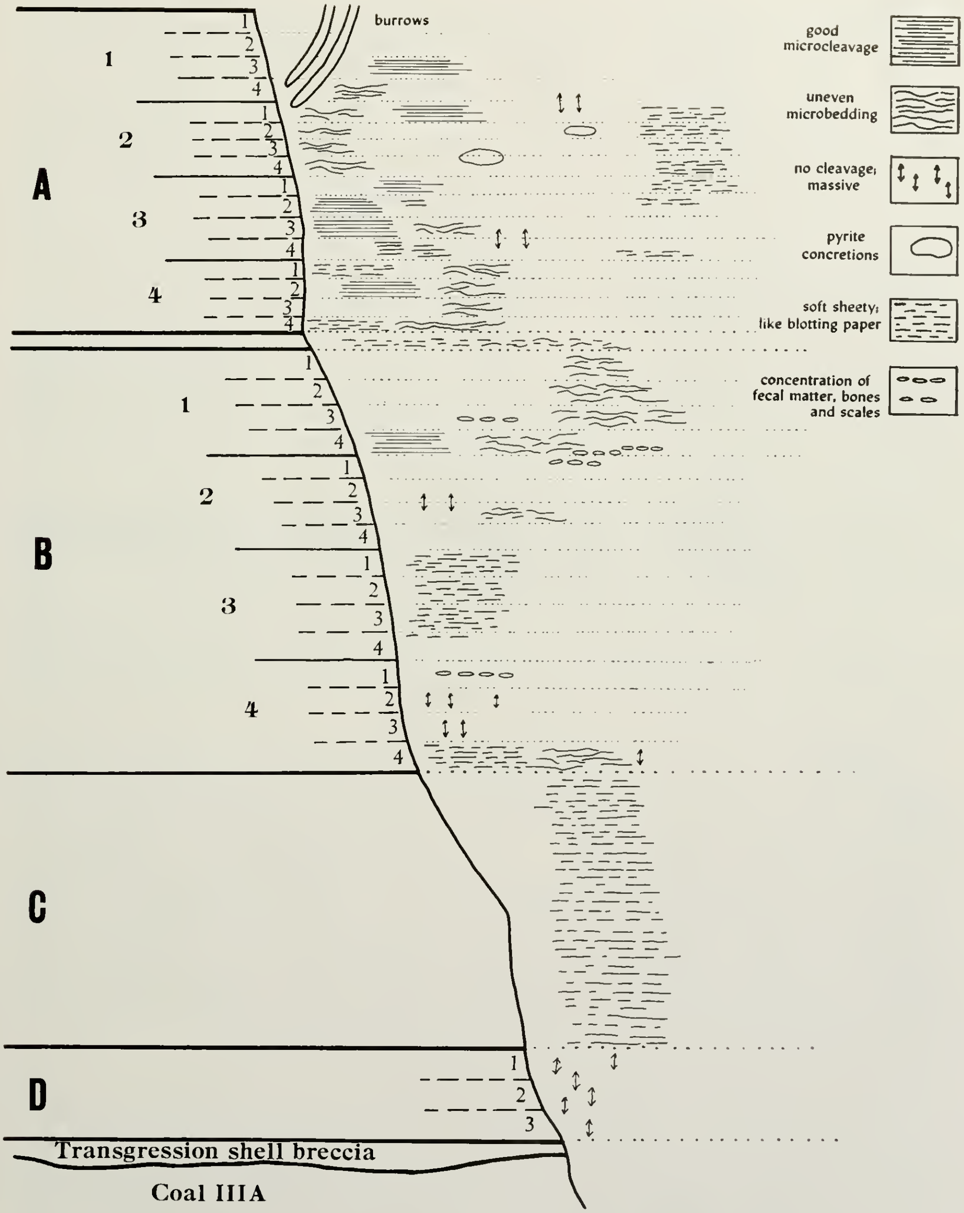
burrows
good microcleavage
uneven microbedding
no cleavage; massive
pyrite concretions
soft sheety; like blotting paper
concentration of fecal matter, bones and scales
A
B
C
D
1
2
3
4
Transgression shell breccia
Coal IIIA

FIG. 2. *Left:* profile of Mecca Quarry shale at Mecca Quarry, showing major and minor stratigraphic divisions and their designations. *Right:* graphic presentation of local shale characteristics (expressed over an area of usually no more than one or two square feet) noted during splitting and charting of quarry sample.

the painstaking process of charting the entire macroscopic fossil content proved to be slow work—all but impossible to accomplish satisfactorily without benefit of laboratory facilities. Hence we decided to remove the entire sample of shale (except for level C, a soft gray shale) to a laboratory at Chicago Natural History Museum, where it was laid out in its original configuration (pl. 2, B). This work was greatly simplified by the fact that the shale was divided by joints into blocks of manageable size. It would have been even easier had these joints extended all the way to the bottom of the shale profile; instead, the joint pattern changed markedly within the profile (see fig. 3, *b*, and pl. 1, B). The joint pattern, as it was first encountered on the surface of the topmost even-bedded shale level, seemed to provide a natural grid for the horizontal and vertical orientation and location of points on the quarry surface. Hence the blocks were serially numbered along the major tiers shown in figure 3, *a*. When the joint pattern changed, it did so in a transitional level where both patterns were recognizable (pl. 1, B). We therefore retained the numbering system by grouping level A numbers in appropriate combinations. This naturally complicated the labeling procedure and the composition of the quarry floor maps for the different levels, but it had no other deleterious effects. The joint pattern of the basal level D was notably more complex than those above; we decided to apply a square grid of appropriate mesh size over it as shown in figure 3, *c*.

Level C, a relatively thick, soft, gray level containing few fossils, could not practicably be moved. It was charted in the field. Embedded in this level was a curiously shaped, large, limy concretion (pl. 2, A); its relation to the surrounding shale was determined, but it was not collected *in toto;* samples taken from it show that it was barren of fossils.

The surface of the coal was uneven. Highly pyritized logs of various sizes were strewn over its surface. These and especially the depressions between them were covered by a buff-colored[1] pyritic clay containing broken shell pieces of a variety of marine invertebrates. We did not remove the coal.

Difficulties were encountered in marking the shale pieces. Before they were removed from the quarry all pieces were labeled as follows: an arrow denoting north, a joint block (or grid) number followed by a level designation. A relatively complicated designation such as this had to be applied by pen point. Ordinary white ink was well suited for the purpose, and produced easily readable labels. It was not, however, waterproof. Since the shale was damp along the bedding planes in the quarry, it was not possible to apply a readily available waterproof coating over the labels. As it was, labels often became faint, and had to be touched up. During periods of rainy weather we applied the labels with yellow pencils. These labels withstood rain, but were difficult to apply to damp shale and were harder to read. In spite of these inadequacies, however, we lost very few labels and the shale bed could be assembled without much difficulty in the laboratory.

2. *MECCA QUARRY: LABORATORY METHODS*

Once the shale was laid out on the floor of a large laboratory at the Museum (pl. 2, B), the time-consuming work of taking a census of its fossil content began. The procedure used throughout this phase of the work was as follows. A piece of shale about one inch thick was removed from the laboratory quarry. Its designation was, for example, 39A1. It was placed on a table label side up (which meant proper stratigraphic position of the slab) and a square grid with a mesh length of 30 cm. was drawn on it with yellow pencil. A similar grid of 10 cm. mesh length was drawn on 17 by 22 inch quadrille-ruled paper and the bound-

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[1] Black where not colored by finely disseminated sulfides.

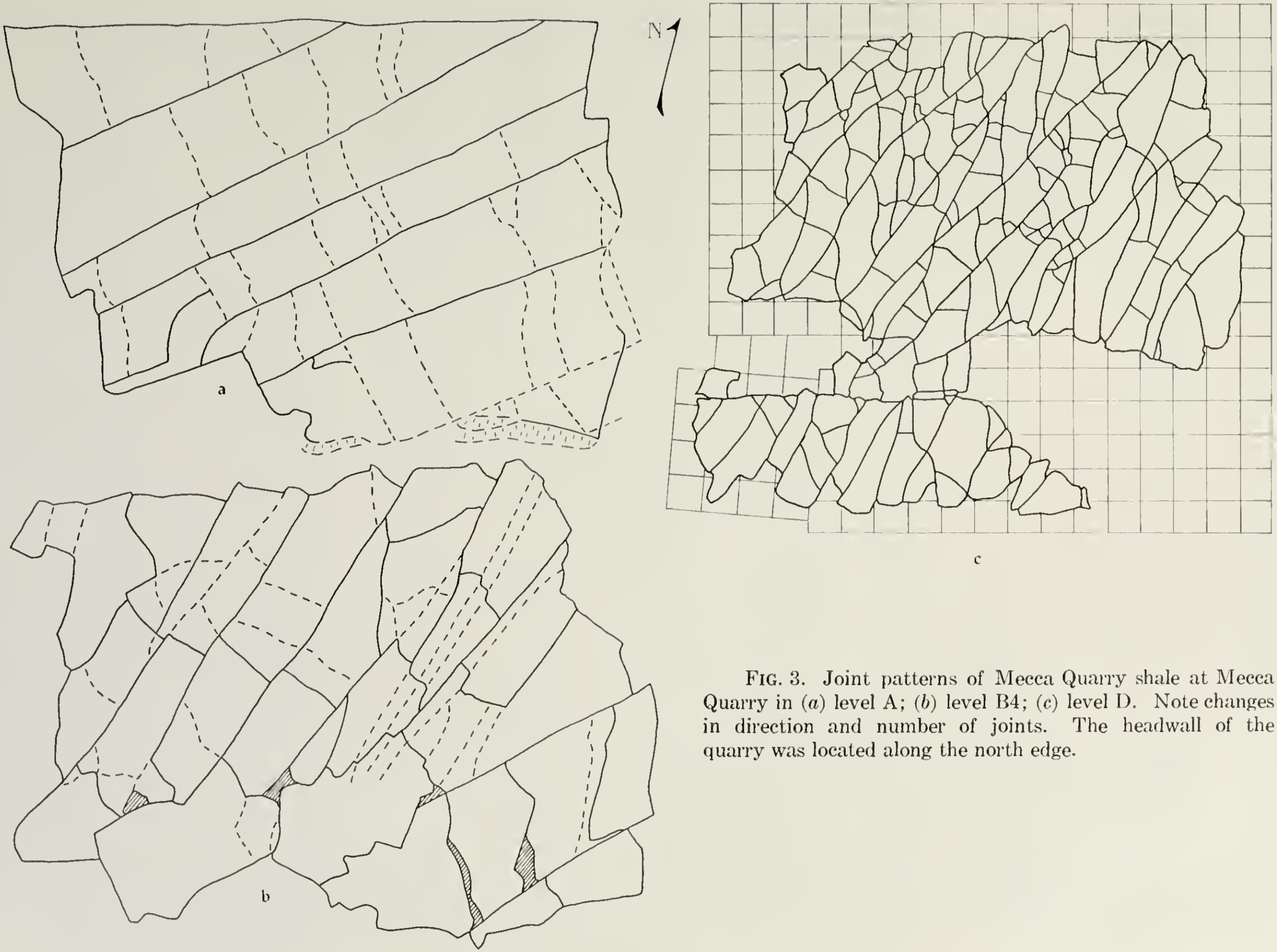

FIG. 3. Joint patterns of Mecca Quarry shale at Mecca Quarry in (*a*) level A; (*b*) level B4; (*c*) level D. Note changes in direction and number of joints. The headwall of the quarry was located along the north edge.

aries of the slab were established on the paper. The north direction was indicated in a corner of the paper, along with the block number, level designation, date, and initials of operator.

The fossil content was charted separately for each of the four quarter-inch levels into which these slabs could be readily split, according to the following scheme: sublevel 1, black pencil; 2, blue; 3, green; and 4, red. Symbols were devised for the common faunal and floral elements:

⊛ = *Petrodus* (placoid scale)
⌀ = palaeoniscoid bone
⟋ = *Listracanthus* (?fin spine)
Ⓢ = shark element (cartilage or tooth)
(Pl) = "placoderm" element (cartilage, bone plate or tooth whorl)
✗ = acanthodian element
⌣ = phyllocarid (piece of test)
◁ = straight cephalopod
@ = coiled cephalopod
⫽ = piece of driftwood

Aggregations of skeletal elements were indicated by dotted lines delineating the approximate horizontal extent of the particle spread and the appropriate designation was put in the center of the area.

All elongated elements, for example *Listracanthus* spines, shark fin rays, acanthodian fin spines, pieces of wood, and straight cephalopods, were entered on the chart in proper orientation relative to north, as closely as this could be determined without actually measuring the angles.

The slab was split by the use of large numbers of steel-handled table-knives ground thin and sharp near the tip of the blades, and struck with rawhide mallets. Once a knife had entered a minor bedding plane knives could be inserted on either side, thus widening the crack for the reception of further knives; by gently tapping all knives in succession it was usually possible to effect a clean split along the bedding plane. Once the ".1" level was loose from the rest of the block, the grid was transferred to the surface of the ".2" level. The fossils visible on both sides of the ".1" level were then entered in black pencil on the chart, and each entry was checked off with a yellow pencil mark on the shale. Then the ".1" level was split farther to reveal the fossils within, and following each split the same charting procedure was followed, until the level had been reduced to rubble. Levels ".2," ".3," and ".4" were handled in the same manner as level ".1," and the fossil content was entered on the chart in the appropriate color. Figure 4 shows a redrawn example of such a chart.

In practice there had to be a lower size limit to the particles that could be charted; isolated palaeoniscoid, acanthodian and shark scales as well as conodonts and spores were neglected. In level D there were innumerable shells and shell fragments of the pectinid *Dunbarella*, the density of occurrence being so great that these could not practicably be charted. Even so, the total number of recorded items amounts to 68,024. It required an average of three operators, working full time, about two years to complete the census. Many isolated elements and all specimens that consisted of an aggregation of more than a single particle were kept for later study. Specimens recognized as bulges on the shale surface were X-rayed rather than split. All were labeled on the stratigraphic upper side with block number and level designation as well as (in most cases) with an arrow pointing north.

A welcome by-product of this laborious census work was the discovery of a number of exceedingly delicate and rare fossils; we are, furthermore, in a position to pronounce with a high degree of confidence that certain fossils do not occur in the shale, for example,

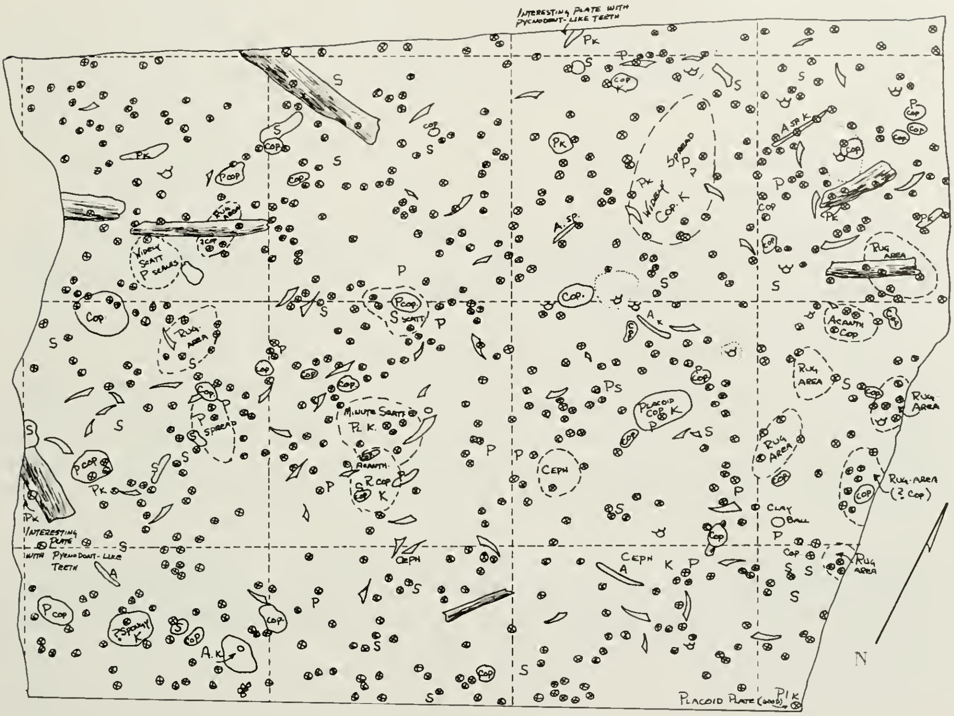
INTERESTING PLATE WITH PYCNODONT-LIKE TEETH
PK
S
P
COP
RUG AREA
VIDEO SCATT P SCALES
P SPREAD
MINUTE SCATT PK
ACANTH
CEPH
PLACOID COP K
A SP K
A SP.
ACANTH COP
RUG AREA (? COP)
CLAY BALL
INTERESTING PLATE WITH PYCNODONT-LIKE TEETH
PLACOID PLATE
N

FIG. 4. An original chart (redrawn) of fossil content of block 13, level B1 of Mecca Quarry. In the original, the fossils in the four sublevels are differentiated by color. The grid is composed of 10-cm. squares (for key to symbols, see p. 12).

insects. Less tangible, but probably of greater importance, was the fact that we gained such intimate knowledge of the physical properties of the various levels of shale that we were able to detect minute qualitative differences between them.

TECHNICAL LIMITATIONS: Any work of this magnitude is bound to be afflicted with some technical limitations. In this case the early charts, made in the field, were too crude and were not used. Fortunately, a satisfactory standard was developed early in the process. The quality of the charts is, however, not completely uniform, partly because a succession of different assistants was used,[1] partly because charting proceeded over a long period of time, and partly because of inherent differences in the splittability of different levels.

In order to gain some idea of the extent to which fossil debris was recovered by the splitting and charting techniques, we X-rayed a few inch-thick slabs before any charting had been done. Then these slabs were processed in the fashion described above, and the charts were compared with the X-ray films. Early tests revealed recovery of 67 per cent of the *Listracanthus* spines and 81 per cent of the *Petrodus* denticles. With improvement

[1] Students of Antioch College, whose work term at the Museum rarely exceeded two months.

of splitting technique the recovery rate was raised somewhat. We feel certain that all of the partially articulated specimens were recovered.

A further check on the validity of the charts resulted from the fact that no one level was charted entirely by a single person. If operator performance was a critical factor, the charts should reflect the differences. With very minor exceptions, however, such differences as may readily be recognized pertain to differences in draftsmanship, rather than in the recording of information.

At the outset, needless to say, the fossil content was known to us only in general terms. Hence no attempt was made to identify species or even genera. In most cases such identification would have been impossible even if the fauna had been well known to us, as, for example, in the case of fragments of cartilage of different sharks.

Furthermore, the nature of the fossil content was not understood at that time. Any small accumulation of disarticulated bones, scales or cartilage was simply designated as "coprolite," with an indication as to the nature of the content: for example, if the aggregation consisted of palaeoniscoid scales and bones, it was called "P-cop"; if it contained cartilage or shark teeth, it was designated as "S-cop." Many of these specimens, as later study revealed, are not coprolites at all, but regurgitated stomach content (see p. 140). In all cases the chart designations are descriptive rather than interpretive.

In combining these data charts into quarry floor maps some difficulties were encountered in levels B3 and B4. This was due to the fact that the joint pattern of A1 (fig. 3, *a*) changed to that of B4 (fig. 3, *b*) and both patterns were expressed together, which resulted in greater fragmentation of the B3 level.

3. *LOGAN QUARRY*

The decision to sample the Logan Quarry shale on a fairly large area was prompted by the discovery of a large articulated shark (pl. 24, B). A surface about 156 feet long by, on the average, about 28 feet wide (about 4000 square feet) was stripped of overburden by running a bulldozer along the right side of the ravine (pl. 3). Since the main interest at this site was the procurement of specimens, the fossil content was not charted; the specimens, however, were provided with accurate microstratigraphic data. The various levels of the shale (see Logan Quarry profile, p. 67) were removed and searched for fossils at the site. The technique of splitting the shale with the aid of numerous knives was the same as that used in the reduction of the Mecca Quarry. Since the density of the fossil content at Logan Quarry was much lower than at Mecca Quarry, it was not necessary to reduce the shale to the same rubble size. As a result an unknown number of specimens was missed. Furthermore, not all of the coprolites or stomach regurgitates were kept. However, we do not believe that this makes any appreciable difference in our estimates of burial density (see p. 167).

4. *GARRARD QUARRY*

In 1960, renewed commercial stripping of overburden in a clay pit about one half mile northeast of the site of Logan Quarry exposed the Logan Quarry shale. Examination of this fresh exposure revealed the presence, at this site, of a fresh-water humulite underlying the transgressive facies of the Logan Quarry shale. The humulite contained a fauna different from that at Logan Quarry (and Mecca Quarry). In view of the fact that the level was to be removed in the course of further stripping, we seized the opportunity to quarry this site over an area about the size of Mecca Quarry (pl. 4). The technical procedure was the same as that used at Logan Quarry; no attempt was made to chart the fossil content. However, we did note local differences in density of fossil content and in the thickness of one level (fig. 17). Careful notes were made of these observations, and shale and humulite samples were collected.

5. *OTHER LOCALITIES*

Stratigraphic work along the outcrop belts of the Mecca and Logan Quarry shales in Parke and Vermillion counties involved careful examination of outcrops, measurements of the coal and black shale sections, and the collection of fossils. In vertical extent the stratigraphic work was delimited at the base by the Minshall limestone and above by the Velpen limestone (see stratigraphic chart, pl. 55). Numerous difficulties were encountered in this work. The effects of weathering on the black shale and humulite tend to obscure or even delete characteristic differences between successive levels. Swelling and splitting along microbedding planes result in thickness measurements that are consistently too generous. The profiles at the discovery site of the large shark and in the bank of an adjoining gully were carefully measured and described. The shale section was again measured and described from fresh rock near the headwall in the Logan Quarry (about 20 feet from the outcrop). There are virtually no similarities between these two descriptions and measurements (see pp. 67–69).

While it is impossible to compare fresh and weathered sections, detailed comparisons between weathered sections are scarcely more satisfactory. On weathered sections it was possible to recognize the typical alternation between soft gray and hard black levels, or between soft and hard black levels, but accurate boundaries between them were never so sharply defined as in the fresh state. For these reasons regional correlation of individual shale levels is possible only in a tentative way.

In the study of the larger profile (Minshall to Velpen limestones) the difficulties were even more notable. For one thing the number of outcrops is relatively small, and few of the ravines in which the profile can be measured are wholly undisturbed by human activity. In virtually every outcrop area there is some evidence of past coal or clay mining and it is often difficult to appraise the extent of the disturbance. In part, at least, this is due to the fact that the soft drab shales tend to creep or slump toward the outcrop faces along the valley sides. Where a part of a coal seam has been removed, the phenomenon is, naturally, more pronounced, but it exists elsewhere also; excellent evidence of this was recently (1961) seen in the newly stripped western portion of the Cayuga Brick and Tile Corporation clay pit, where there is notable marginal slumping of drab shales and coal seams toward the valley of Coke Oven Hollow (fig. 15).

Rarely were notable portions of the profile seen in vertical outcrop. Most often the profiles had to be measured along the stream valleys with resulting uncertainties as to the thicknesses, especially of the drab shale units, because of local dips. In many instances plane table work was necessary, and even this did not always result in satisfactory solutions to local problems.

Nowhere was the entire sequence of beds from the Minshall to the Velpen limestones seen in continuous section. Most often only a small portion of the sequence was exposed. Since nearly all depositional features in this sequence are repetitive, it is extremely difficult to determine the stratigraphic position of the observed beds. In many instances an outcrop area was repeatedly visited, and invariably additional valuable information was obtained. It should also be pointed out that many geologic features were seen during but one visit, having since been covered by silt, exposed by erosion, or modified by human activity; many observations are thus no longer verifiable except by excavation.

6. *LIGHT REFLECTIVITY MEASUREMENTS*

The Mecca Quarry shale consists of alternating bands of black and gray shale. Since there is a clear correlation between the density of the fossil content and the relative blackness of the shale (fig. 39) it seemed desirable to establish the relative grayness of the various quarter-inch levels by some objective means. The technique devised involved the measurement by a light-sensitive instrument of the light reflected from the surfaces of shale samples. Several shale samples of each one-quarter inch level of the Mecca Quarry shale profile were ground smooth, but not polished, parallel to the bedding planes. The samples were then mounted on glass slides with the ground surfaces parallel to the glass. The instrument used was a Densichron, a very sensitive light meter, in conjunction with a simple vertical bellows camera from which the lens mount had been removed and replaced by a Leitz Ultropak incident light illuminator. The receptacle containing the photoelectric cell was taped to a piece of stiff cardboard of proper size to fit into the plate-holder of the camera. A specimen of shale was then placed under the camera and the Ultropak optics were so arranged as to produce an out-of-focus image at the level of the photoelectric cell, covering about a circular quarter-inch area of the specimen.

Next we sampled many specimens in order to find one that showed virtually no lateral variations on repeated tests over its entire surface. This sample was designated as the control, and the entire procedure as well as the performance of the instrument were checked with this control slide after every third reading.

Once the technique had been worked out satisfactorily, the shale samples were systematically processed. Two or more readings were obtained from the surface of each sample, depending on the amount of variation that was recorded from different parts of the shale surface. The entire suite of samples was measured on two different occasions, and the results were reasonably comparable.

The above technique, serviceable though it was, has some inherent limitations. The shale, even within one-quarter inch levels, is rarely uniform in composition and thus in color. In grinding parallel to the bedding planes we may have stopped at light or at dark microbands, a variable that was somewhat compensated for by the use of several samples of each level. It is unlikely that we would have ground to the same plane in all of them (fig. 5 and Table 1). Grinding vertical to the bedding was tried and abandoned because it was almost impossible to achieve the same readings twice as the circular light spot emitted from the Ultropak exceeded one quarter inch in diameter and thus extended beyond the edges of the specimens.

The instrument performance, once the technique had been developed, was excellent. Such difficulties as occasional fluctuations in line voltage resulted in extreme readings which could be ignored after several consistent readings were made with the specimen left in the same position. Care was taken, however, when a new bulb was used in the Ultropak, because of the marked drop in intensity during the initial burning phase.

7. *THIN SECTIONS*

Thin sections of both shale and fossils were made. While the preparation of thin sections of fossils presented no more problems than usual for this type of material, the shale samples had to be ground extremely thin before they became translucent enough to

TABLE 1.—REFLECTIVITY MEASUREMENTS, MECCA QUARRY SHALE

Stratigraphic level	Number of readings	Total (in arbitrary units)	Average reading	Charting value
A1.1	17	327.7	19.3	4.5
.2	6	109.7	18.3	3.5
.3	7	137.3	19.6	4.5
.4	7	140.1	20.0	5.0
A2.1	11	236.6	21.5	6.5
.2	21	453.1	21.6	6.5
.3	14	332.2	23.7	8.5
.4	7	151.6	21.7	6.5
A3.1	14	304.4	21.7	6.5
.2	8	191.2	23.9	9.0
.3	20	478.2	23.9	9.0
.4	17	381.6	22.4	7.5
A4.1	16	379.7	23.7	8.5
.2	23	522.9	22.7	7.5
.3	23	544.3	23.7	8.5
.4	34	787.1	23.2	7.0
B1.1	19	467.0	24.6	9.5
.2	23	529.0	23.0	8.0
.3	21	508.4	24.2	9.0
.4	8	196.6	24.6	9.5
B2.1	18	468.3	26.0	11.0
.2	17	450.3	26.5	11.5
.3	22	608.9	27.7	12.5
.4	25	691.5	27.7	12.5
B3.1	31	645.0	20.8	6.0
.2	25	518.1	20.7	5.5
.3	27	564.8	20.9	6.0
.4	24	519.4	21.6	6.5
B4.1	15	408.4	27.2	12.0
.2	29	715.8	24.7	9.5
.3	16	365.5	22.8	8.0
.4	15	347.0	23.1	8.0
C	24	364.1	15.2	0.0
D1	23	556.1	24.2	9.0
2	16	421.1	26.3	11.5
3	6	144.4	24.1	9.0

Average reading	Charting value	Average reading	Charting value
15	0	21	6
16	1	22	7
17	2	23	8
18	3	24	9
19	4	25	10
20	5	26	11
		27	12

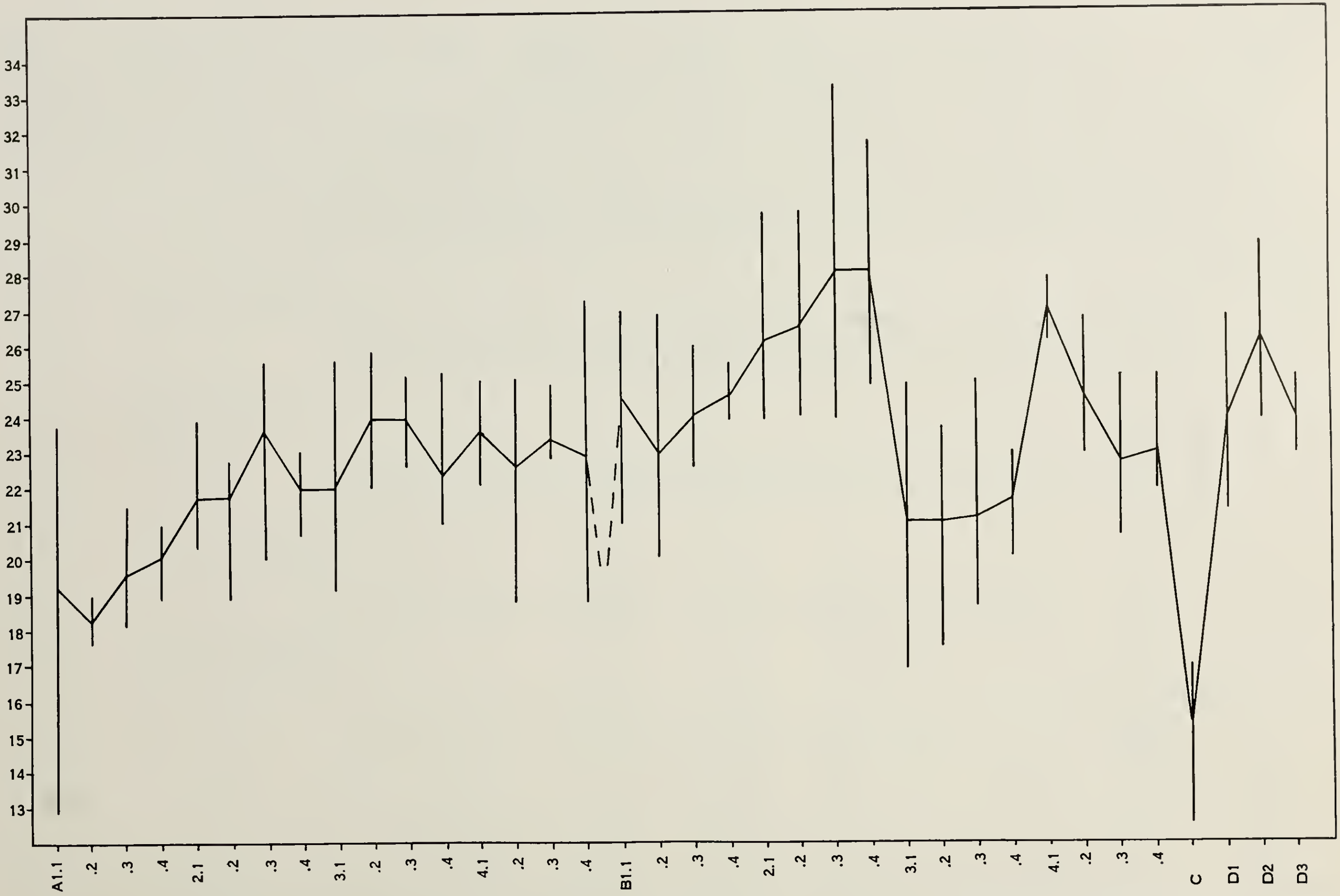

FIG. 5. Relative blackness of microstratigraphic levels of Mecca Quarry shale at Mecca Quarry. Vertical lines indicate range of observed values; continuous line connects calculated mean values.

be serviceable. The usual technique of fastening the ground and polished surface of the specimen to a glass slide by means of Collolith, gum damar, or Lakeside 70 and then grinding to desired thickness invariably resulted in the loss of the specimen as it became thin. The difficulty was finally overcome by use of a clear epoxy resin, Araldite (product no. 6005, with hardener no. 951[1]), which has remarkable adhesive powers and which permitted grinding to extreme thinness. Some levels, especially those containing large quantities of opaque material (similar if not identical to micrinite in coal) had to be feathered out on one side to permit examination at different thicknesses.

The technique is relatively simple. A piece of shale was sawed to the desired size with a separating disc on a flexible shaft. It was then ground smooth on a glass plate, using a fairly fine-grained abrasive and water. After it had thoroughly dried, it was mounted, smooth side down, on a glass slide with a drop of Araldite. The specimen must not be pressed too firmly to the glass; it should be moved slightly back and forth on the glass slide to make sure that there are no bubbles between specimen and glass and to remove excess Araldite. The Araldite sets hard within 24 hours at room temperature, after which time the thin grinding may proceed. Besides its great adhesive power this mounting medium has another advantage. If a specimen is mounted in the way described, there will be a little mound of Araldite along the edges of the specimen, perhaps a quarter of a millimeter thick. Araldite does not grind as readily as does the shale. Thus when the specimen has been ground down to the level of the Araldite mound along its periphery, further grinding proceeds slowly and there is plenty of time to check the thin section as it gradually gets thinner. All grinding was done by hand, with a circular motion.

There was no necessity to impregnate the black shale samples. The gray levels, on the other hand, were impregnated (to the degree possible) with gum damar in a vacuum oven. The rest of the technique followed the procedure described above. Only in a very few cases was it necessary to omit water in the grinding process. In these cases alcohol was used and the results were satisfactory. The thin-grinding of fossils, including coprolites, invariably required impregnation with gum damar in a vacuum oven at a temperature of about 105° C. The rest of the technique was the same as that described for the shale.[2]

The study of gastric residues and coprolites did not require thin-sectioning of the specimens, although a few such sections were made. In most cases it sufficed to cut the specimen in two or three pieces (usually vertical to the bedding planes). The cut faces were ground smooth and protected by a coat of diluted gum damar or Duco cement. This treatment initially brightens the surface to good advantage, but in time, unfortunately, darkens it. The removal of these coatings with appropriate solvents must be done with the utmost care, since the shale tends to warp and crack if it is submerged in acetone or xylene, benzene, or toluene.

8. *RADIOGRAPHIC METHODS*

The Mecca and Logan Quarry shales are readily penetrated by X-rays. This is a most fortunate circumstance, since the standard techniques of preparation of fossil materials, if applied to these black shale fossils, require an extraordinary amount of time. Without the possibility of surveying the fossil content by means of radiographic processes, this study could not have been undertaken. Virtually the whole fossil content, except for isolated elements, was X-rayed. Other exceptions were specimens that had been split along the bedding planes in which they lay, thus exposing them on plate and counterplate. For the biostratonomic problems at issue in the present study, X-ray pictures of the specimens are often far more meaningful than the specimens themselves.

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[1] Ciba Products Corporation, Fairlawn, New Jersey.

[2] The technique described by Tourtelot (1961) could not be tested, since the description was published after our work had been completed.

The radiographs were made on non-screen medical X-ray film. At a current density of 5 milliamperes, kilovoltages ranging from 40 to 75, depending on the grayness and thickness of the shale slabs, were necessary. The exposure time most often used was 30 seconds. Target distance was 43 inches. As silt is less transparent to X-rays than organic matter, gray levels required the higher KV settings.

In order to render the radiographs more readily comparable, paper prints were made with the aid of a "LogEtronic" printer, an electronic dodging device. All the study prints are direct prints from the negatives; the prints here reproduced, however, have been obtained from intermediate negatives—a method that permits greater control of the overall picture contrast.

9. *PHOTOGRAPHIC METHODS*

Field photographs and those of larger specimens were made with a variety of ordinary photographic equipment. Small specimens or small areas of larger specimens were photographed with a Microluminar (Winkel-Zeiss, 36 mm.) attached to an ordinary vertical bellows camera.

The photomicrographs were made with a Zeiss Planapo 10/0.32–160– objective and Kpl. 12.5× ocular, on Eastman Panatomic-X film.

10. *METHODS USED IN THE STUDY OF MODERN BLACK MUD ENVIRONMENTS IN LOUISIANA*

a. Sediment Samples: Sediment samples were obtained in a variety of environments in Louisiana (p. 114) where black muds are being deposited. Most of these samples were taken close to the sediment surface, probably no deeper than 3 or 4 feet below the mud surface. The mud was examined, within hours, in the laboratory at Tulane University.

Some of the mud of nearly all samples was permitted to settle out on coarse filter paper and the samples were immediately dried between sheets of newspaper, in a drying box. Other samples were bottled and imperfectly sealed. In this condition they were left to dry up over a long period of time. Some of the dried samples have since been sectioned by the same technique as that used for shale samples, using alcohol instead of water for the grinding process. The mud in these bottles obviously underwent further bacterial (probably mostly anaerobic) decomposition, and is not thought to be representative of the muds accumulating in the collection areas. The sections, however, do provide interesting points of comparison with the shale sections.

b. Leaves in Process of Decomposition: Many leaves and leaf fragments in various stages of decomposition were collected from the surface of the bayou muds. These were dried as herbarium specimens. For purposes of identification modern plants along the bayous were also collected and dried. Some of these leaves were embedded in paraffin and sectioned with a microtome.

c. Fish Decomposition Experiments (see p. 167): Certain observations on fish skeletons in the Mecca and Logan Quarry shales suggested the desirability of information concerning the mode and speed of bacterial (particularly aerobic) decomposition of fishes in black mud environments at relatively high temperatures.

For this purpose several identical containers were built, consisting of tubes of fine-meshed copper screen secured and closed off, fore and aft, by removable circular plastic discs. Freshly killed fishes were placed in these cages and the stocked containers were permitted to settle on or beneath the surface mud at a number of selected stations in Louisiana waters. The date and time as well as depth of submersion were recorded, along with temperature measurements of both water and air, the pH of the interstitial water of the surface mud, the salinity, the character of the mud and a description of the locality (Table 6). When the experiment was terminated the containers were retrieved, the contents preserved in 10 per cent formalin, and all the above measurements and observations repeated.

C. THE REGIONAL SETTING OF THE MARGIN OF THE ILLINOIS BASIN

During Pennsylvanian time, the Illinois Basin was already a well-defined and even ancient structural feature of the continent (Eardley, 1951, p. 32). Surrounding and enclosing this basin as well as the Michigan Basin to the north and others to the west was an area that received a considerable thickness of sediment but without sinking so greatly or so continually as the basin proper; this has been designated the "shelf" (Krumbein and Sloss, 1951, p. 341). It merges into the basin through a "transitional zone" (Potter and Glass, 1958, p. 9) which includes Parke and adjacent counties in Indiana, the area of the present study. These three regions are structural rather than physiographic provinces.

The rock sequence of the rapidly subsiding portion of the basin is about twice as thick as that in the transition zone, which is in turn about twice as thick as that on the shelf proper (see fig. 6). In the rapidly subsiding basin there are, in addition, stratigraphic units not represented on the flanks, being interpolated between some of the units of that area (Wanless and Weller, 1932).

Pennsylvanian deposition began (Caseyville–Mansfield) with clastic deposition filling in and smoothing out the moderately rugged relief previously developed on the pre-Pennsylvanian surface. At about the time of the Minshall coal and limestone—the earliest of the beds examined in our sections—the rate of subsidence of the basin increased, and coal seams and marine deposits became a prominent part of the record. Potter and Glass (1958, p. 49) have presented a useful analysis of the depositional history at this time in terms of shifting physiographic provinces: "A coupled low-lying coastal plain and marginal shallow shelf appears to provide the best large-scale model of the environment of deposition. . . On such a physiographic couple, oscillations of strand line would be far-reaching, near-shore marine, littoral, tidal flat, and nonmarine sediments all could occur, opportunities for coal bed formation would be plentiful, and the development of erosional channels preceding sandstone deposition would be commonplace."

The sea frequently entered the sinking basin from the southwest, and at times when the sinking was faster than depositional filling of the basin, it occupied the basin or overflowed across the coastal plain. The direction to the open sea is particularly well shown by the westward thickening of limestones (Wanless, 1955, p. 1800), by the direction of sandstone-filled channels (Hopkins, 1958; Potter and Simon, 1961; Andresen, 1961), and by the southwestward thinning of coal beds (e.g., Coal 2 of Illinois, IIIA of Indiana: Wanless, 1955, p. 1790). We make the suggestion (see fig. 51) that the transgressing sea paused on at least two occasions in Parke County after occupying the basin and before overrunning the coastal plain. This is consistent with the greater number of stratigraphic units in the basin, in indicating that the structural edge of the basin served recurrently as a physiographic boundary in Middle Pennsylvanian time.

The depositional record of the Pennsylvanian system is characterized by cyclically repeated sequences of beds, the unit cycles being the cyclothems of Weller (1930). Many interpretations of the origin of cyclothemic deposition have been offered (Beerbower, 1961). It seems logically necessary to postulate that the Illinois Basin was tectonically downwarped to accommodate the great thickness of sediments. Furthermore, interfingering of facies indicates that the rates of sinking and of sediment accumulation were not equal and not uniform. Both must have accelerated periodically. Periods of minimal rates of sinking and clastic deposition are indicated by coals and limestones. Our own evidence requires no further postulates to account for the cyclothems in our area of study.

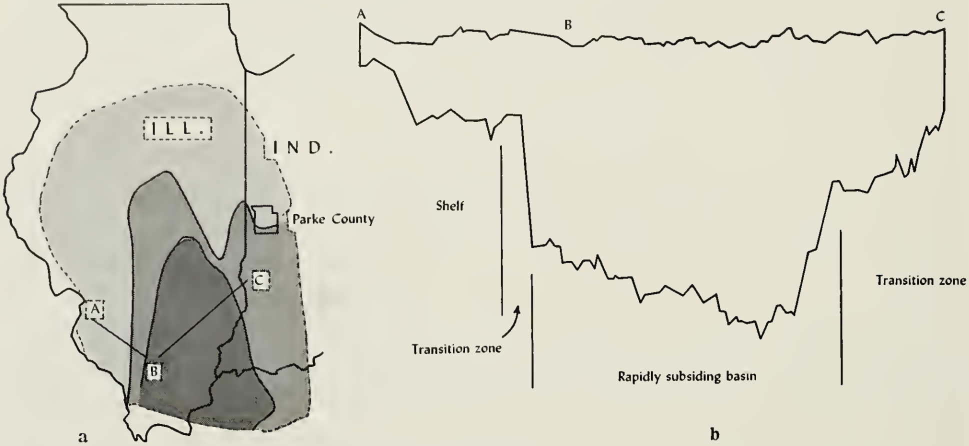

FIG. 6. Illinois Basin: (*a*) areas of different rate of subsidence (after Potter and Glass, 1958, fig. 2, B); (*b*) cross section (after Wanless, 1955, fig. 14).

Detailed reconstruction of the paleogeography on a regional scale is hampered by lack of any time-marker bed, such as a volcanic ash, and by lack of information on rates of deposition. However, it seems clear that at any time when coal was being formed in Parke County there were marine conditions somewhere to the southwest and that in the opposite direction there lay relatively higher land whose plant cover was not being preserved as coal because it was oxidized above the water table. With continued crustal sinking and sedimentation, these three zones—marine, coal, and upland—moved back and forth toward and away from the sea. Such is the general picture; thanks to abundant evidence preserved in several successive beds of black shale, we are able to fill in details in that part of it that concerns the first few years of flooding as the sea moved inland across the coal swamp.

The four black shale horizons with two of which we particularly concern ourselves record with remarkable completeness a repeated transgressive history. Fischer (1961) has pointed out that as a sea transgresses across marginal lagoonal facies (as on the modern New Jersey coast), the high-energy open sea environment will normally destroy the sedimentary record of the lagoonal phase. Fischer (op. cit., pp. 1664–65) has applied his New Jersey observations to Illinois-type cyclothemic deposits, picturing a widespread lagoonal environment approximately coextensive with the Illinois Basin during both transgression and regression: "As sea-level rose and the waters encroached on a land of very low topography, dotted with large subsiding areas such as the Illinois and Michigan basins, these negative areas first became huge swamps, and later vast bays, separated from the main seaways by tectonic barriers (sills, peninsulas) and by spits and barrier beaches. Here the terrigenous muds were trapped, and shales and occasional fine-grained limestones, with brackish to marine faunas, were deposited. When such areas were very effectively silled, temperature or salinity stratification developed, and led to the deposition of black mud."[1]

Fischer points out a marked difference between the two examples, namely, that as the Pennsylvanian water advanced onto the coastal plain, the encroaching sea did not destroy the record as happens in New Jersey. He ascribes this to "the much greater scale —in width and depth—of the Illinois 'lagoons'." In a "lagoon" of the scale of the Illinois Basin there is a large reach across which winds can stir up appreciable waves. Yet the evidence of the sediments, and particularly of the transgressive black shales, demands postulation of extremely quiet water. Moore (1929) suggested that the water was too shallow "for circulation and effective wave or tidal agitation," and he modified this later (1950) in picturing "a kind of marine swamp in which seaweeds grow so thickly that disturbance of the bottom by wind and waves is nil."

The sheety black shales that we have studied show that there was virtually no bottom disturbance of any kind at the time of their deposition. They all represent the initial phases of transgressions, lying immediately over coal beds or underclays. In at least some localities each of these shales contains a characteristic fauna which we call the Mecca fauna (see pp. 122–125).

To judge from the literature, the Mecca fauna is not universally present in the black shale lying on coal; we know it only on the basin margin, in the "transition zone" (fig. 6). The black shale, however, is much more extensive than that part of it that contains the Mecca fauna, having been deposited throughout the basin. "Lateral extent of some of the black shale bodies is more than 100,000 square miles. . . ." (Moore, 1950.) Apparently the only elements of the Mecca fauna contained in the central-basin area of the black shale are *Petrodus, Listracanthus,* and *Pseudorthoceras,* with perhaps palaeoniscoid fishes. The margin of the basin, then, was in some manner environmentally different from its central part. We have a certain amount of evidence that the "vast bay" formed by the flooding of the basin may have been limited to the basin proper at certain times in a period of relative "stillstand" before overflowing onto the shelf (see discussion, p. 31, of productid reefs and bayou channels); thus there was probably opportunity for a large population of a fauna peculiar to the bay margin to develop prior to the transgressions. Ashley and Ashley (1899, p. 133) have picturesquely referred to this as an "advance guard fauna," explaining it as "a fauna which, from a greater ability to move rapidly into new territory, would be the first to appear after an invasion of the sea."

The question of depth of water in the basin, along the basin margin, and on the newly submerged coastal plain is a complex one. Our evidence relates only to the latter, but permits inferences as to the conditions in the basin as well. Very soon after the Logan transgression began there was sufficient depth to permit navigation by large sharks as much as 13 feet long (pl. 24, B), and, somewhat later, by coiled nautiloids three feet in diameter. Extremely shallow water throughout the basin at the time of the initial marine invasion across the coastal plain would certainly have prevented these members of the fauna from approaching the shore zone. Yet there is strong evidence that on the newly submerged coastal plain the water was extremely shallow, actually only inches deep in the "black band" phase of level J at Logan Quarry (see p. 69). Our evidence indicates that the water fluctuated rhythmically in depth.

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[1] As will be developed below, we do not believe that actual physical silling is a prerequisite for the formation of black muds.

By way of solution to the problem of shallowness of water, broad extent of black shale deposition, availability to large marine animals, source of black organic matter, and various other factors, we offer the concept of an intricate archipelago-bayou topography with a cover of vegetation (*flotant*) on the water. No matter how flat a land surface may be, it is never a geometrical plane: "Most of the newly-emerged sea bottoms lack a little of perfect flatness." (Fenneman, 1938, p. 36.) *A fortiori*, the surface of a coal swamp must have an irregular topography which, when overrun by shallow water, will present the appearance of a confused mass of islands. At the earliest stage of inundation, bayous and inlets would be conspicuous. One of these in our Pennsylvanian profile is well exposed in cross section at Montgomery Creek (p. 39, fig. 9); in a space of 50 yards, the subaqueous surface here had a relief of about a foot and a half.

During growth of the coal swamp, the "land" surface was covered (or nearly covered) with shallow water in which plants grew and vegetable matter accumulated (see Neavel, *infra*, p. 204). The water was derived from local rainfall and from drainage of the distant hinterland; it ran over the swamp in a sheet and through it in channels (Friedman, 1960). Thus the physiography was comparable to that of the Dismal Swamp of Virginia. In the Dismal Swamp, the slope of the surface of the swamp water itself is one foot to the mile; its gradient is maintained by interplay of local rainfall, the gravitational tendency to run off, and the obstruction to flow offered by the dense vegetation. In the Everglades, where obstruction to runoff is provided only by sedges and occasional tree-covered hummocks, the gradient is still two inches per mile (Fenneman, 1938, pp. 36, 63). If the vegetation density and rainfall in the Pennsylvanian coal swamp were in any way comparable to those parameters of the Dismal Swamp—and it seems reasonable that they were—the swamp surface between channels must have been in the form of low interfluves with a comparable surface slope. Inundation of such an irregular surface would result in an intricate shore zone with low islands on the "seaward" side and bayous and channels penetrating the "landward" side. It is precisely such a topography that the distribution of fossils and lithologies has led us to postulate in the Parke County coastal plain zone. A shoreline with this appearance exists on the southwest of the Florida peninsula, constituting the physiographic province known as "The Southwest Coast and Ten Thousand Islands" (Davis, 1943, figs. 1, 14). Like the postulated Pennsylvanian shore zone in Parke County, this area is formed by transgression of a sea across a swamp based on a deep peat deposit. However, the resemblance is only superficial, as the offshore islands of the Florida area are largely constructed on shellfish bars.

D. STRATIGRAPHY

In the sections that we have examined in Parke County and vicinity, we find a distinctive fauna of elasmobranchs, paleoniscoid fishes, acanthodians, "placoderms" and associated invertebrates in the characteristic black sheety shale overlying several coal beds. The "Mecca fauna," as we shall designate this assemblage, recurs at least four times in the Brazil, Staunton and Linton formations, in the black sheety shale; in addition, at one of these levels, in the Staunton formation, another characteristic assemblage, the "humulite fauna," occurs in pyritic humulite, representing a pre-transgression, non-marine environment. The Mecca fauna and the humulite fauna occupied, respectively, the seaward and the landward sides of the shore zone.

TABLE 2.—CORRELATION CHART OF STRATIGRAPHIC UNITS BETWEEN MINSHALL AND VELPEN LIMESTONES

Series		Group	Formation	Cyclothem	Members and coals			
Midcontinent	Appalachians	Wier	Wier	Alexander, 1944	Wanless, 1939	Friedman, Core 33	Friedman, 1960	This paper
Des Moines	Allegheny	Carbondale	LINTON	LIVERPOOL		(unnamed)	Velpen limestone	Velpen limestone
						(unnamed)		Mecca Quarry shale
					Coal IIIA (Upper Hanging Rock coal) (Velpen coal)	Coal IIIA	Coal IIIA	Coal IIIA
		Tradewater	STAUNTON	GREENBUSH	Coal III (Lower Hanging Rock coal) (Staunton coal)	Coal III	Coal III	Coal III
				Upper WILEY	(two Rock Creek coals)	(probably equivalent to Lower Lodi coal)	(two unnamed coals)	Lower Lodi coal
				Lower WILEY	? Seahorne limestone	(unnamed)	Silverwood limestone	Logan Quarry limestone
						(unnamed)		Logan Quarry shale
						(unnamed)	Staunton A coal	Logan Quarry coal
				Upper DeLONG	Holland limestone	(unnamed)	Holland limestone	Holland limestone
						(unnamed)		Holland black shale
						(unnamed)		Holland coal
				Middle DeLONG		(unnamed)	(unnamed)	Coal IIA
Atoka	Pottsville		BRAZIL	SILVERWOOD	Coal II	Coal II?	Coal II	Coal II
				MINSHALL	Minshall limestone	Minshall limestone	Perth limestone	Minshall limestone
					Minshall coal		Minshall coal	Minshall coal

The Mecca fauna appears to have been restricted at any time to a narrow belt immediately along the shore. It has been observed in the Parke County area, Indiana, and in Kankakee and Knox counties, Illinois, all in the "transition zone" (fig. 6) and at the Brazil to Linton levels. In other stratigraphic and geographic positions, the black shale facies commonly yields fossils of *Petrodus* and *Listracanthus*, two of the elements of the Mecca fauna, but the other components have rarely or never been recorded.

Most of the stratigraphic sections below have been visited in a search for clues to the lateral extent of the Mecca fauna in the Mecca Quarry shale and the Logan Quarry shale. In general, sections have been measured as they outcrop; that is, without digging to expose unweathered rock. In most lithologies, this makes little difference, but there is a notable difference in the appearance of the black shales in the weathered and the unweathered conditions. This was forcefully brought to our attention in the Logan Quarry section, where we carefully measured the stratigraphic profile exposed in a steep valley wall, and then measured it again after having dug a quarry into fresh rock at the same place. Although the black shale remained black shale, we could not recognize the subdivisions as the same in the weathered and unweathered profiles. Sections derived from the literature often cite figures for thickness of black shale differing from those we measure today—undoubtedly the result of the difficulty of recognizing black shale in the weathered profile, and of the difficulty of distinguishing it in some cases from coal and from the gray shale that commonly overlies it.

1. *DEFINITIONS OF NEW STRATIGRAPHIC UNITS*

Four new stratigraphic units, the Mecca Quarry shale member and the Logan Quarry coal, shale and limestone members must be proposed before describing the individual stratigraphic sections. The Velpen limestone (of authors) is more precisely characterized as a member, in keeping with established usage. Comparative stratigraphic columns of the Minshall to Velpen interval are given in Table 2.

a. MECCA QUARRY SHALE MEMBER: The Mecca Quarry shale, proposed as a member of the Linton formation of Wier (1950), consists of evenly bedded sheety alternating gray and black carbonaceous shale lying upon Coal IIIA and beneath a marine shale and limestone that have been correlated with the Oak Grove member in Illinois and the Velpen limestone member in Indiana (Wanless, 1939, p. 24; Wier, 1952, p. 13). The shale varies from very dark black to a mottled medium gray, both facies generally with excellent cleavage parallel to the bedding, so that it may be split into sheets often thinner than a millimeter. The elasticity of the blackest beds is such as to allow cleavage of sheets of several square feet without breakage. In the type section, one inch above the bottom of the member, there is a bed of soft gray shale about three inches thick containing large calcareous concretions that may be several feet in length and more than a foot in thickness (pl. 2, A). Smaller pyritic concretions occur in some of the black levels, but large "niggerhead" concretions are not found in these levels. The bottom layer of the Mecca Quarry shale is commonly a thin transgression shell breccia, consisting of pyritized broken shells in a black carbonaceous clayey matrix without bedding. The transgression breccia, normally ranging from a thin film to a few inches in thickness, may thicken laterally into a channel "clod"[1] nearly two feet thick, consisting of an unbedded gray to black carbonaceous clay with an abundance of marine invertebrates.

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[1] This term, more commonly used in the nineteenth century than in recent years, is listed in the American Geological Institute's Glossary as "a term applied by miners to loosely consolidated shale commonly found in close conjunction with a coal bed"—a definition attributed to Kay.

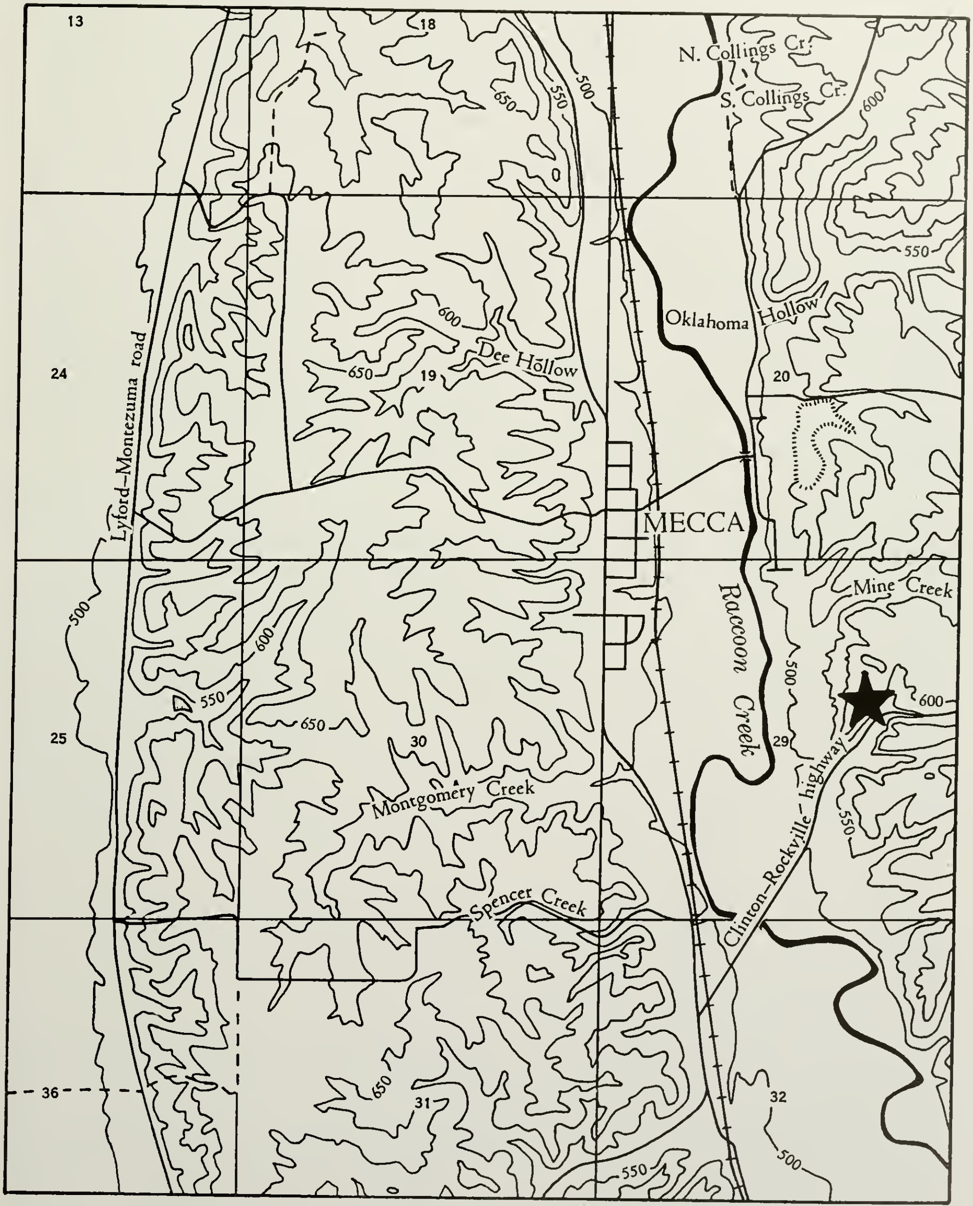
13
18
N. Collings Cr.
S. Collings Cr.
650
550
500
600
550
Oklahoma Hollow
600
Dee Hollow
650
19
20
24
Lyford–Montezuma road
MECCA
Mine Creek
Raccoon Creek
500
500
600
600
550
650
30
29
25
Clinton–Rockville highway
550
Montgomery Creek
Spencer Creek
36
650
31
32
550
500

FIG. 7. Map of Mecca area. Star indicates location of Mecca Quarry. Scale: 2½ inches= 1 mile.

We define the Mecca Quarry shale to include all varieties of evenly bedded gray and black shale and channel clod lying between Coal IIIA or its position, if it is missing, and the Velpen limestone and shale member above. The top of the Mecca Quarry shale is distinguished with difficulty. Above the evenly bedded sheety black and gray shales, commonly containing the Mecca fauna, there is a transition to unevenly bedded friable gray to blue to buff clay-shale with a normal marine invertebrate fauna. In the transition beds a burrowing infauna makes its appearance, heralding the influx of the normal marine fauna in the beds above. Ecologically, the introduction of the infauna marks the end of the special environment that trapped the Mecca fauna (p. 45) and thus might be taken as limiting the top of our stratigraphic unit. However, the sheety bedding of the shale commonly continues into the deposits of this changed environment. Since the character of the bedding is readily recognized in the field, the top of the Mecca Quarry shale as a lithologic unit is placed at the top of the sheety shale. The type locality of the Mecca Quarry shale member of the Linton formation is a small quarry dug for the purpose of this study in Wabash Township, Parke County, Indiana (SW¼ NE¼ Sec. 29, Twp. 15 N., R. 8 W.), about a mile from the town of Mecca (figs. 7 and 10). This quarry has now been obliterated by the slump of the hillside above it, but a band of Mecca Quarry shale is exposed on the sides of gullies in the immediate vicinity.

b. VELPEN LIMESTONE MEMBER: A small distance above the top of the Mecca Quarry shale as defined above, there occurs at least one thin bed of limestone, the equivalent of the Oak Grove or Velpen limestone. The Oak Grove limestone has recently been redefined as a member of the Lowell cyclothem, "consisting of interbedded limestone and shale. It is designated as a limestone because its most distinctive elements are limestone and it occurs at a position in the cyclical sequence normal for a limestone." (Kosanke *et al.*, 1960, p. 35.) The Velpen limestone is not so clearly defined. First used informally by Dunbar and Henbest (1942) as "Velpen cap" in a columnar section, and again by Cooper (1946) as "Velpen limestone" in another columnar section, it would appear to refer only to a limestone bed. However, it is not a simple bed of limestone, particularly in the area of this report, where it resembles the Oak Grove member in containing two or more thin limestones separated by drab shale. Thus we include in this member the unevenly bedded shale between the sheety shale of the Mecca Quarry member and the limestone, as well as the limestones themselves.

Typically, the Velpen limestone member may be recognized in this area by two thin bands of limestone in outcrops, a short distance above the black Mecca Quarry shale. These are very well exposed at West Montezuma (see p. 59) and at Montgomery Creek (see p. 41). However, the Logan Quarry limestone can locally assume the same appearance as, for example, at Dotson's Branch (see p. 91).

c. LOGAN QUARRY SHALE MEMBER: The Logan Quarry shale member is proposed as a unit of the Staunton formation. It lies upon one of the hitherto unnamed local coals of the Staunton, about fifty feet below Coal IIIA in our Barren Creek section (p. 37). Like the Mecca Quarry shale member, it consists of alternating hard black sheety shale and soft dark gray sheety shale. At the type locality, these shales lie upon a poor coal about four inches thick; here and elsewhere they contain fossils of the Mecca fauna. The top of the Logan Quarry shale is taken as the highest of the sheety shales, gray at the type locality; above this there is usually a poorly bedded blue-gray shale containing a normal marine invertebrate fauna, which we include in the Logan Quarry limestone member.

In the type section, we recognize a succession of beds identified by letters from "F" through "K" ("I" was not used) within the Logan Quarry shale. These are described in the stratigraphic section of Logan Quarry (p. 67). Some of them can be recognized in other exposures of the member, level G being particularly persistent. The lithology of the Logan Quarry shale is more variable from one exposure to another than is that of the Mecca Quarry shale. In the type locality there are only three black and three gray beds; in others there are four of each. At Garrard Quarry, about a half mile northeast of Logan Quarry (p. 69), there is in addition a dense black waxy to coaly poorly bedded humulite and a very finely bedded green humulite consisting of alternate laminae of finely divided pyrite and shiny black plant degradation material (fig. 16, Zones 4–6).

The type locality of the Logan Quarry shale is a quarry in Reserve Township, Parke County, Indiana (NE¼ SW¼ Sec. 9, Twp. 16 N., R. 8 W.), about 1¾ miles east of West Union, near the head of one of the hollows draining into Sugar Creek (fig. 15). The quarry is named for Mr. P. H. Logan, of Indianapolis, who gave us permission to dig it on his property for the purposes of this study. About one-half mile northeast of Logan Quarry (NE¼ NE¼ Sec. 9) is a large clay pit operated for the Cayuga Brick and Tile Corporation by Mr. Gerald Garrard, of West Union, where the Garrard Quarry fresh-water facies was exposed in 1960 and 1961. The "Garrard Quarry" existed briefly near what was then the southwest corner of the clay pit. Although Garrard Quarry no longer exists, exposures of this interesting facies may be seen in Trumpet Valley and vicinity, a few miles to the north (see map, fig. 19).

d. LOGAN QUARRY COAL MEMBER: Many of the coals in the Staunton formation were deposited in small local basins and consequently have very limited distribution. Whether these minor coals may be followed from one outcrop to another is a problem that can be settled only by continuous exposures or closely spaced drill holes. A coal lying beneath the Logan Quarry shale has been called the "Staunton A" coal (Friedman, 1960), but it is not certain that this is a single, continuously developed coal. For convenience in correlation within the area of this report, we prefer to call it the Logan Quarry coal member. At Logan Quarry, it is a poor coal of drifted sticks, varying in thickness from 2¾ to 6 inches. At Garrard Quarry, about six inches of poor coal lie at the base of the section, probably the equivalent of the Logan Quarry coal. Beneath the Logan Quarry coal at Logan and Garrard Quarries is a thin black clay; at Logan Quarry it contains marine invertebrates. This lies upon the underclay and may represent a reworked underclay with organic matter worked into it.

The type locality of the coal is the same as that of the Logan Quarry shale member.

e. LOGAN QUARRY LIMESTONE MEMBER: This member is homologous with the Velpen limestone member, occurring in the same relation to the underlying black sheety shale and coal. At the type locality it includes a bed of impure, dark-gray, carbonaceous, argillaceous limestone from 8 to 10 inches thick, containing brachiopods, crinoid fragments, and other typical marine invertebrates. Beneath the limestone is a 2-foot bed of dark blue-gray unevenly bedded clay-shale lying upon the sheety shale of the Logan Quarry shale member. At other localities, such as at Dotson's Branch, the limestone may be represented by two thin beds with drab shale between, or may die out laterally by change of facies to a calcareous shale. Both the limestone and the interpolated (if any) and subjacent shale are included in this member, by analogy with the Velpen limestone member; but the top is defined, at least provisionally, as the top of the highest limestone bed.

The type locality of the Logan Quarry limestone member is the same as that of the Logan Quarry shale member.

2. *FACIES WITHIN THE BLACK SHALE PROFILES*

Black shale is a readily recognized unit in the cyclical sequence of beds in the Pennsylvanian. In general, in the sections under consideration here, it is readily cleaved parallel to the bedding and contains a large proportion of organic matter. This is recognized in the common appellation of this rock in the older reports as "bituminous slate." The term "carbonaceous sheety shale" is preferable. In a recent review article, Dunham (1961) calls attention to several types of occurrence of black shale throughout the world, citing conclusions of several authors on their mode of origin. Black shale obviously may form in a variety of ways. In the sections we have studied, only one of these modes of origin accords with all the evidence, namely, deposition in a shallow transgressing sea with anaerobic conditions present at the bottom. In addition, we are impressed by several lines of evidence pointing to a widespread mat of vegetation covering the surface of the water near the shore (see p. 121). The abundant fauna, the evidence of anaerobic bottom conditions, and the evidence of the mat of floating vegetation force us to conclude that the water was stratified (see diagram, fig. 27). To this concept a study of the microstratigraphy within the black shales adds support.

Field inspection of the shales reveals a great range of gray, dark gray, and black color; a range of structure parallel to the bedding from almost perfect fissility to virtually uncleavable massiveness; and luster of the fractured surface ranging through degrees of waxy, satiny, charcoaly, dull, and glassy (in coalified stems). An analysis of the various beds in terms of three constituents helps to systematize these differences. In the composition diagrams (fig. 25) of the Mecca Quarry shale and the Logan Quarry shale, the opaque organic, translucent organic, and clay mineral constituents of the shales are charted for each of the minor stratigraphic levels within the respective profiles. A positive correlation between gray color (as opposed to black) and clay-mineral content is immediately apparent. Fissility is probably the result of the presence of microbanding within the shale, massiveness the result of its absence. Luster of the fracture surface varies with the content of opaque versus translucent organic particles, and, of course, with the clay minerals. Abundance of fossils was early seen to coincide with the blackness of the shale—a field observation that is expressed in detail by the chart (fig. 39) based on blackness. The values of blackness for this chart were derived, as related in the section on techniques (p. 16), from a measure of the amount of light reflected from a standard light source by small blocks of shale ground to a standard matte surface.

The principal feature of the relatively gray beds is the relatively high ratio of clay minerals to organic constituents. Obviously, clay was introduced into the locus of deposition during deposit of the gray beds. To arrive at a depositional site in the marginal area of the sea it must have been introduced either from the nearby land or, by reworking, from the sea floor farther out. In either case it must have been carried by currents. But we have abundant evidence in the nature of the bedding and the fossil distribution on the bedding surfaces that there were no appreciable currents along the bottom. On the other hand, it is clear that oxygenated water lay over deoxygenated water, the animal population living in the upper level. Throughout the sedimentary profile the condition of the carcasses indicates active predation in the overlying water, the poisonous lower water layer not having mixed vertically upward. In the absence of currents on the sea bottom and of vertical mixing, what can be the source of the clay? It is introduced from elsewhere, so it must have been carried by a current. As the current is not on the bottom, can it be on the top? The actual surface, according to our well-substantiated hypothesis, was occupied by a floating mat of vegetation, but there is no reason to suppose that the aerated and densely populated water layer beneath it did not carry a slight current. It is commonly observed that off the mouths of rivers a current of fresh water flows out to sea for a long distance without mixing with the salt water, held in place by its lower specific gravity and higher temperature. This current is available for transport of clay without disturbance of the bottom sediments. The notable fluctuation in the amount of clay in the Mecca and Logan Quarry profiles is correlated with depth of water; very large cephalopods in level F at Logan Quarry, a gray level, indicate water several feet deep, while the near desiccation in the black level J at that place during preservation of a large elasmobranch carcass (pl. 24, B) points to very shallow water.

The alternation of gray and black beds in the shale sequence is conspicuous in the lower part of the Mecca Quarry shale member but becomes less marked with each alternation, until at the top of the member the dark gray level A1 simply grades into the overlying gray marine shales. Throughout levels A, B, and C the various elements of the Mecca fauna are well represented, more abundantly in the black levels and less so in the gray. But the number of specimens of all members of the fauna diminishes upward through level A, finally disappearing, except for *Pseudorthoceras*, in the unevenly bedded dark gray shales of the transition between the Mecca Quarry shale proper and the marine shales of the Velpen limestone member above. Thus, aside from the fluctuation in clay-to-organic ratio in levels C through A, the habitable environment remained about constant, gradually altering in the transition beds to a normal marine environment. From this, it appears that the amount of organic material available to the sediments was approximately constant through this time, but fell off as the marine Velpen environment developed. In other words, the *flotant* was constantly present. Fluctuating amounts of clay were superposed, producing the facies change from black to gray.[1] But as time continued, each increment of clay produced less and less effect, until in level A the black-gray fluctuation becomes nearly imperceptible. This we take as evidence of deepening of the water, so that the area in question came to lie in effect farther and farther offshore, and thus received a progressively more diluted contribution of the stream-carried clay that was largely deposited close to the shore. The alternation of gray and black beds coupled with the periodic influx of clay and the evidence of deeper water during gray level deposition accords with other evidence indicating a type of climate characterized by alternating rainy and dry seasons (p. 172). Recognition of color differences in the general category of black shale, reinforced by petrographic study of the various color facies, is thus a strong tool for paleogeographic reconstruction.

An entirely different facies that likewise may be lumped with the black shales in field work is the black "channel clod." We have observed this principally in the Linton formation, where it commonly lies upon Coal IIIA. It is a structureless black to gray clay, typically with very abundant marine invertebrate fossils occurring in lenticular, presumably elongate bodies as much as two feet thick. Where fossils are very numerous, the clod has a horizontal "grain" that is not truly bedding. This facies is particularly well exposed at Montgomery Creek and West Montezuma (see diagrams, fig. 9). Ashley (1899, p. 33) interpreted some clods as deeply weathered black limestones, but it is evident from many of his reported sections that he had seen the clod in the same position as we have, lying upon the coal, where limestone is not developed. The invertebrate fauna of the clod is the same as that found in the limestones and the normal light-colored marine shales higher up in the section. Laterally, the channel clod pinches out into a thin "transgression shell breccia" composed of broken shells, commonly pyritized, in the same structureless black clay matrix.

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[1] Alternating layers of black and gray sediments in a modern environment, though a deep-water offshore site of deposition, have been similarly interpreted by Orr *et al.* (1958, p. 946): "These observations suggest that the gray layers are zones of rapid sedimentation of the inorganic components (silts and clays) which mask the normal deposition of organic materials. . . . Just below each gray layer the pheophytin content is slightly greater than just above the gray layer and it is tempting to speculate that this came about because the underlying layers were rapidly buried . . . and thus did not undergo the normal amount of decomposition on the bottom before burial."

Like the gray beds in the black shale sequence, the channel clod is a fruitful source of paleogeographic information. The channel lay upon the peat but was not cut into it by erosion, as the thickness of the coal beneath it is very close to that lateral to it. Neavel shows (*infra*, p. 210) that the coal beneath the clod-filled channel at Montgomery Creek was deposited in a wetter environment than the coal adjacent to the channel, and thus that the channel was already a topographic low during peat accumulation. With the first pulse of subsidence, the sea flowed inland into the existing topographic lows. In the channel at West Montezuma, among many shells lacking spines, clumps of the productid *Desmoinesia muricatina* are preserved with their delicate spines interlocked and unbroken (pl. 23, A). On the other hand, most of the shells in the Montgomery Creek channel are broken, as they also are in the widespread thin transgression shell breccia. This introduces a problem in reconstruction of the two environments. Neavel shows (*infra*, p. 199) that the coal below the channels at the two places is strictly isochronous. Thus the more westerly channel, at West Montezuma, was not occupied before the other. It is more reasonable to conclude that the marine environment in which the productids had been living up to the moment of transgression lay very close to West Montezuma and had lain there for a long enough time to allow small productid banks or reefs to develop. Then, with an incursion of the sea water into the bayous of the peat swamp, blocks of these banks might have been carried a short distance without damage to the individual shells, while those that were carried farther inland suffered greater damage.

Dunbarella shale: In the Mecca Quarry sequence, the first stage in the development of the black shale is a massive but thin bed, level D, characterized by a great abundance of the scallop *Dunbarella*. Individuals of this species characterize the lower units, L and Kb, of the Logan Quarry sequence, where the marine transgression began. The *Dunbarella* shale also follows upon the pond environment of the Garrard Quarry humulite fauna. In the Logan Quarry sequence at Big Pond Creek, *Dunbarella* occurs through more than three feet of black shale immediately succeeding the coal. In all cases, the *Dunbarella* occurrence is followed by the efflorescence of the Mecca fauna, though this is scantily developed at Big Pond Creek and at Haworth Creek.

Dunbarella, a free-moving pelecypod, is typically found in black shales (Newell, 1937), though we have seen specimens in limestone, and others in limestone are reported by Chernyshev (1960) from the Donetz Basin. Elias (1937) reported that flat-shelled pelecypods, including the pectinid *Aviculopecten*, characterize shallow-water deposits in the Permian Big Blue series of Kansas. Since the *Dunbarella*-bearing black shale of our sequences always occurs either directly upon the coal or a very short distance above it, it is clear that here too *Dunbarella* inhabited shallow waters. Although some modern pectinids are abundant in shallow water and even occur in large numbers on mud flats, others inhabit fairly deep waters of normal salinity. Associated with *Dunbarella* in the black shales above the coals are other thin-shelled pelecypods and *Pseudorthoceras knoxense*, a ubiquitous straight-shelled cephalopod. The *Dunbarella*-bearing shale is uniformly a very dark black, with poorly developed bedding, suggesting slightly disturbed water at the time of deposition. Its upper surface, however, is an unusually smooth flat bedding surface, above which *Dunbarella* does not occur.

Humulite: Humulites are found in many outcrops of the Logan Quarry shale beneath the transgressive sheety black shale. Humulite greatly resembles shale in appearance, splitting characteristics, and fossil content, but its composition is that of a coal (see p. 113, "microscopic components"). Within this lithologic type one may distinguish a range of characters from black, waxy, unevenly bedded to olive green, finely laminated. In weathered state it is virtually unrecognizable, having turned into granular, sooty muck often with an efflorescence of fine acicular gypsum crystals intimately mixed with powdery yellow elemental sulfur. The humulite contains a fresh-water fauna (pp. 122–125) and characteristic thick, dark brown elongated coprolites.

3. *DESCRIPTION OF STRATIGRAPHIC SECTIONS*

The stratigraphic sections that follow are arranged, so far as possible, in a south-to-north sequence, and may be located by reference to the map (fig. 1). Correlation is based largely on Core 33 of the Indiana Geological Survey, used by permission, as described by Samuel Friedman in the log of that core on file with the Survey.

ROCK RUN: Rock Run, a major tributary of Raccoon Creek, occupies a broad valley of fairly low gradient extending approximately from Rockville to Coxville. In its lower course it runs under some prominent bluffs of Coxville sandstone, one of these being the type locality of that member (Friedman, 1960, p. 24). About a mile above the mouth of the valley, the stream enters the thick channel-fill phase; farther upstream are exposures of Coal III and Coal IIIA in the banks (Sec. 10, T. 14 N., R. 8 W.). Coal IIIA is overlain by the Mecca Quarry black shale, sheets of which are prominently noticeable in the creek bed below the outcrop belt. At an exposure of Coal III, the following section is seen, somewhat disturbed by small normal slip-faults:

LINTON FORMATION		
Coxville sandstone member		
STAUNTON FORMATION		
Gray clod-like clay with pelecypods and brachiopods	1′	
Coal III	1′	9″
The bottom 2 inches of the coal is shaly, containing fusain and grading upward into the coal. The coal has much brown attritus and fusain, with stringers and blobs of bright anthraxylon.		
Underclay	at least 2′	

At the southernmost outcrop of Coal IIIA, the coal and black shale dip downstream at a greater angle than the gradient of the stream. Where they lie above water level, the section is:

LINTON FORMATION			
Velpen limestone member			
Alternating thin limestones and shales		at least 6′	
Mecca Quarry shale member		2′	3¼″
Soft dark gray to black fairly evenly bedded shale (level A-plus)	6″		
Alternating soft gray and hard black sheety shales with Mecca fauna (levels A and B)	10″		

Soft gray well-bedded shale (level C) with a thin hard dark layer	10″	
Hard black massive to sheety shale (level D) with abundant *Dunbarella*	1¼″	
Coal IIIA		8″

About 1400 feet up the last tributary that enters Rock Run, the Velpen and Mecca Quarry members are again well exposed (Sec. 16, T. 14 N., R. 8 W.). Beneath the coal, the underclay is dark gray, grading downward to nearly white plastic clay and then to micaceous silty clay, thin-bedded sandstone, and massive Coxville sandstone.

Core 33: This core was drilled in 1956 by the Indiana Geological Survey in the Mecca quadrangle (SE ¼ NW ¼ SW ¼ Sec. 5, T. 14 N., R. 8 W.). The following condensed description is taken from the detailed lithologic description by Dr. Samuel A. Friedman, on file with the Indiana Geological Survey, and is used here by permission. Stratigraphic designations are in part ours.

LINTON FORMATION		
Velpen limestone member?		
Shale, light gray to medium gray, clayey, with a few thin ironstone concretions		11′ 5½″
Velpen limestone member		5′ ¾″
Limestone	2½″	
Shale, dark gray, clayey, with ironstone concretions	2′ 5½″	
Shale, gray-black, well-bedded, with abundant fish remains	1′ 6½″	
Limestone	10¼″	
Mecca Quarry shale member		
Black shale, evenly medium- to thick-bedded, with abundant minute fossil fragments		2′ 5″
Coal IIIA		1′ 7½″
Coal	11½″	
Shale parting	¾″	
Coal	7¼″	
Underclay		5′ 6¾″
Sandstone		3′ 4½″
Shale, light gray, grading downward to medium blue-gray; fossil impressions, probably fish, at base		4′ 11¼″
STAUNTON FORMATION		
Coal III		4′ 5¾″
Coal	3′ 6¾″	
Clay parting	8¾″	
Coal	2¼″	
Underclay		2′ 6″
Shale and siltstone, drab		30′ 8″
Coal, "probably equivalent to Lower Lodi coal"		1′ 8½″
Underclay, shaly in middle		7′ 4½″
Logan Quarry limestone, black to dark gray, thick-bedded, with abundant white *Microconchus*		4″
Logan Quarry shale member		
Black to gray, medium- to thin-bedded, with abundant brachiopods(?) and a coiled nautiloid. Calcareous in top 4 inches		2′ 8¾″
Logan Quarry coal		1′ 8½″
("Staunton A; equal to an upper Staunton coal at Coal Bluff, Vigo County")		

Shale, gray-black to black, silty, micaceous, carbonaceous, with fossil shell(?) impressions (equivalent to level M at Logan Quarry?)		6″
Underclay and shale		11′ 8″
Holland limestone member		
Tan, sub-lithographic, dense, with abundant white fossil fragments		3½″
Holland black shale member		
Black, thin- to medium-bedded, carbonaceous; calcareous at top and bottom; coalified logs in basal 10 inches		4′ 10½″
Underclay		3′ 6″
Limestone, light tan-gray, medium-bedded, sublithographic (? position of Coal IIA)		7¼″
Shale, medium dark gray, with 1 foot, 4 inches of black shale at 1 foot, 2 inches from top; ironstone concretions		12′ 4¼″
BRAZIL FORMATION		
Shale, black, thin-bedded		½″
Coal II		9¼″
Shale, black, massive, carbonaceous, tough ("bone coal")		½″
Underclay, medium dark gray		5′ 5½″
Shale, medium dark gray		1′ 2¼″
Minshall limestone member		18′ 4″
Limestone	3′ 1″	
Shale	2′ 2¼″	
Limestone	13′ ¾″	

SOUTH FORK, TURTLE CREEK: Exposures on this creek, while not very satisfactory, give us our southernmost measurement of the Logan Quarry shale sequence, at about 520 feet elevation. Where the Logan Quarry limestone crosses the creek, there is a small structure with a dip of 11° to the northeast (striking N. 45° W.). The name "Turtle Creek" is our appellation for an otherwise unnamed geographic feature.

STAUNTON FORMATION		
Gray shale		
Lower Lodi coal		4¾″
Underclay and gray to blue shale		2′ 10″
Covered		about 1′
Sandstone, with plant fragments		1′
Covered, with gray shale at the bottom		about 3′
Logan Quarry limestone member		1′ 7″
Limestone	4″	
Gray to blue shale, partly covered (level E?)	1′ 3″	
Logan Quarry shale member		2′ 6½″
Black to gray friable soft shale	5″	
Black soft sheety shale	1½″	
Dark gray soft sheety shale	4¾″	
Hard black sheety shale (level G)	4″	
Gray soft well-bedded shale (level H)	6¾″	
Hard black massive to sheety shale (level J)	1½″	
Dark gray poorly bedded shale	3″	
Dark gray moderately well-bedded shale	2½″	
Shaly coal or coaly shale (humulite?)[1]	1½″	
Logan Quarry coal (thin)		
Underclay		

[1] When we measured this section, we had not yet become familiar with the humulite facies.

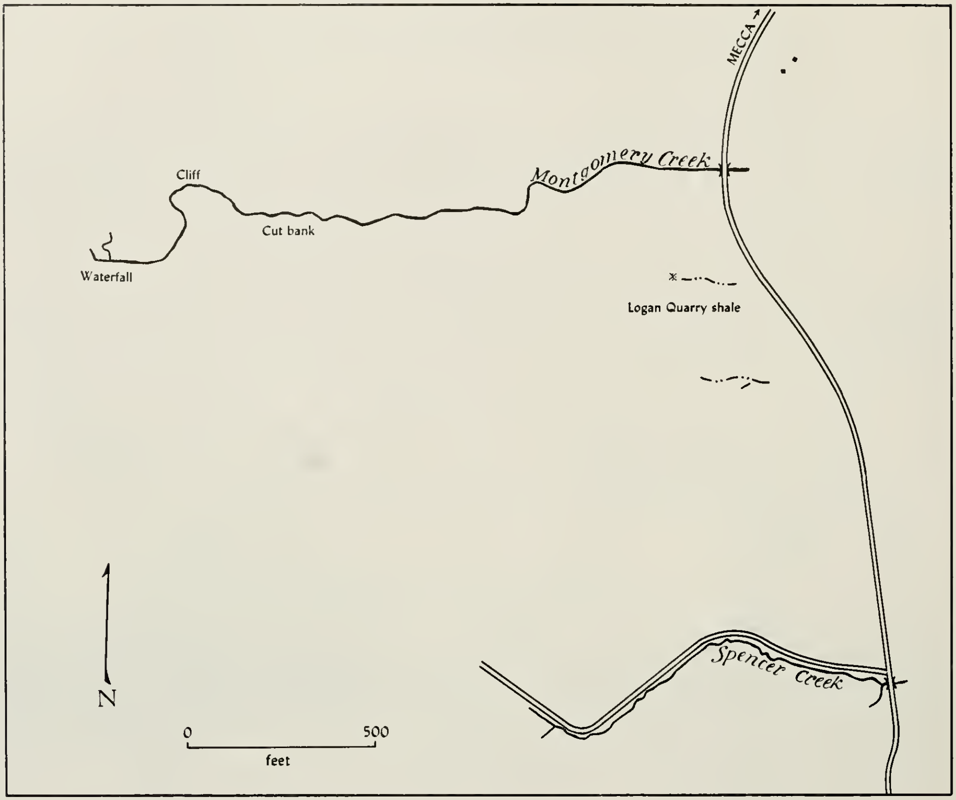


Fig. 8. Map of Montgomery and Spencer Creeks, from plane table traverse.

Spencer Creek: Coals III and IIIA, with associated strata, are exposed alongside the road that crosses the divide between the Raccoon Creek and Wabash River drainages, about a mile south of Mecca, in the valley of a small unnamed stream (see map, fig. 8). We have used the name of Spencer Creek from the circumstance that the stream lies on the land of Mr. Alex Spencer. The following section is compiled from measurements of exposures in several of the small "gopher-hole" mines that have penetrated one or both of these coals. The section recorded by Ashley (1899, p. 372) at Dixon Bank is no longer well exposed.

LINTON FORMATION		
Shale, dark gray to drab, poorly bedded. Transition from Velpen limestone member to Mecca Quarry shale member		3¼″
Mecca Quarry shale member		1′ 4¼″
Level A-plus: shale, hard, black, moderately well-bedded At the top is a hard solid layer.	4½″	
Level A: shale, soft, black to gray, well-bedded	4″	
Level B: shale, hard, black to gray, well-bedded	4″	
Level C: shale, soft, gray, well-bedded Concretions such as are found in this level at other localities were not observed.	3″	

Level D: shale, hard, black		¾″	
Transgression shell breccia, a film			
Coal IIIA			9″ to 1′ 6¾″
Coal	2½″	11¾″	
Parting	¾″	¾″	
Coal	5¾″	6¼″	
Underclay			6′ 7″
Blue, weathering to yellow-ochre		2′ 7½″	
Gray, sandy, with concretions		2′ 11½″	
Coxville sandstone member			11¾″

This sandstone readily correlates with the thick sandstone near Coxville, interpreted by Friedman (1960) as a delta and channel deposit formed early in Linton time. On the other hand, it also correlates with the sandstone between Coals III and IIIA at Montgomery Creek (see p. 43), which appears to lie below rather than above an unconformity.

STAUNTON FORMATION

Shale, gray, sandy to clayey	1′ 7¾″
Coal III	1′ 11¾″ to 2′ 9½″
Underclay	

Barren Creek: Ashley (1899, p. 378) recorded a 42-foot section on the Cox and Bascom places in the lower Linton and upper Staunton formations. We have examined the section at this place several times, entering the valley through a farm belonging to Mr. Frank Haworth of Rockville (near the north line of Sec. 33, T. 15 N., R. 8 W.). The creek has no name locally, and we have called it Barren Creek for our own reference, alluding to the paucity of fossils in the well-exposed sheety shale. Exposures in this valley are excellent, but the construction of a stratigraphic column encounters the usual difficulties attendant upon traversing for a considerable distance horizontally. The interval between the Lower Lodi coal and Coal IIIA was checked by a side traverse up a steep slope, with a minimum of horizontal displacement in the measurement. The upper two units in the following section are taken from Ashley, our observation including nothing above the Mecca Quarry shale.

LINTON FORMATION

"Gray shale"		10′
"Band of ironstone (place of limestone)"		2″
We have seen a hard, dark, impure limy bed in this position, containing crinoid fragments and brachiopods.		
Mecca Quarry shale member		
Alternating hard black sheety shale and soft gray sheety shale, with very scarce elements of the Mecca fauna		1′ 1″
Levels A and B	8½″	
Level C, with concretions	3¾″	
Level D, with *Dunbarella*	¾″	
Transgression shell breccia, of variable thickness, becoming laterally a channel clod with bellerophontids, crinoids, productids.		
Coal IIIA		1′ 7¾″
Coal, with hard fusain on top	1′	
Clay parting	¾″	
Coal	7″	
Underclay, becoming drab shale beneath.		

STAUNTON FORMATION

Drab shale, including underclay at base of Linton formation		10′
—Position of Coal III—		
Underclay (a few inches, included in unit beneath)		
Drab to blue shale, with concretions in lower part		26′
Within this shale are two sandstone lenses, the higher one 4 feet thick, about 2½ feet below the position of Coal III, the lower one about 4 feet beneath the other, 5 inches thick. Both pinch out laterally in a short distance. The upper part of the shale beneath the lower sandstone is sandy.		
Shale alternating black and gray soft friable		1′ 8″
Channel clod		4″
Unbedded black carbonaceous mudstone with fossil invertebrates.		
Laterally, the black and gray shales and the channel clod are replaced by blue shale continuous with the overlying unit.		
Lower Lodi coal		1′ 10″
Underclay		about 2′
Blue shale with concretions		7′ 6″
Logan Quarry limestone member		6″
Dark gray muddy limestone, weathering readily, with sections of large crinoid stems	3″	
Blue shale, soft, clayey where weathered	3″	
(Corresponding to level E of Logan Quarry)		
Logan Quarry shale member		about 2′ 6″
Black hard and soft sheety shale. A partial vertical exposure showed 1 foot, 10 inches; a complete section exposed along several yards of the stream course exhibited 3 feet, but as the softer layers of the sheety shales are particularly subject to swelling when wet and weathered, this latter thickness is certainly too great. *Dunbarella* in lower levels.		
Logan Quarry coal		3″
Dark muddy shale or mudstone		4″
(Corresponding to level M of Logan Quarry)		
Underclay		6″ to 9″
Sandstone		3′
A lens, varying in thickness where seen from 2 feet to 4 feet, 3 inches, always directly overlain by the underclay.		
Drab shale, mostly covered		9′ 9″
About 2½ feet below the overlying sandstone is another thin sandstone lens a few inches thick, exposed as two hard bands with sandy shale between.		
Holland limestone member		5½″
Hard dense light tan limestone, dying out laterally by facies change.		
Drab shale		2′ 4″
Where the Holland limestone is absent, this shale is continuous with the shale above the limestone.		
Holland black shale member		8′
Black to dark gray friable to fissile shale. Of this thickness, only the top foot is a black sheety shale. Laterally, the black shale appears to be replaced by a gray unevenly bedded shale.		
Shale, dark gray to blue, unevenly bedded		5′
Coal IIA		5″ to 1′ 9″

It is interesting to note that at this locality, where the Mecca Quarry shale is abundantly exposed but notably barren of fossils, the Logan Quarry shale is likewise anomalously developed, apparently lacking the usual gray sheety shale levels, and the persistent Holland limestone dies out laterally.

J. S. STRONG PLACE: This is probably an exposure alluded to by Ashley (1899, pp. 367, 378) as exhibiting the same section as was then exposed on the John Daniels place one-third of a mile north. We visited the outcrop in 1959, with Charles E. Wier, Richard C. Neavel and Harold C. Hutchison of the Indiana Geological Survey, and found the Mecca Quarry shales very well exposed at an elevation of about 590 feet.

LINTON FORMATION			
Velpen limestone member			
Ashley reported 5 feet of gray shale.			
Mecca Quarry shale member			1′ 4 5/16″
Level A		4 1/16″	
Level A1	1 1/16″		
Level A2	15/16″		
Level A3	1 1/16″		
Level A4	1″		
Gray shale layer		3/8″	
Level B		4 7/8″	
Level B1	5/8″		
Level B2	1″		
Level B3 (expanded by weathering)	2″		
Level B4	1 1/4″		
Level C		5″	
Level D, with *Dunbarella*		1 1/4″	
Transgression shell breccia		3/4″	
Thickness variable; from a mere film on top of the coal, it thickens laterally to 3 inches. Where thickest, it is a black channel clod deposit, replacing both the transgression shell breccia and level D.			
Coal IIIA			1′ 7 3/8″
Coal		9 1/2″	
Pyritic clay		3/8″	
Coal		9 1/2″	
Underclay			
About 2 feet thick, with Coal III, about 6 inches thick, beneath it.			

MONTGOMERY CREEK: Ashley (1899, pp. 372–373) recorded three good sections in the valley of this unnamed tributary of Raccoon Creek, on the Montgomery and Laferty properties. In order to have a name by which to refer to our measured sections, we have taken the name of Montgomery, former landowner of the lower course of the stream. The exposures on the former Laferty land are particularly important from a paleogeographical viewpoint in that they display good cross sections of a marine channel or narrow estuary lying upon Coal IIIA. We did not see the reported dying out of Coal III (Ashley, 1899, p. 373), as this is in a position between our "cliff" and "waterfall" exposures (see fig. 9) and is now covered with forest soil. Farther up Montgomery Creek than the exposures of

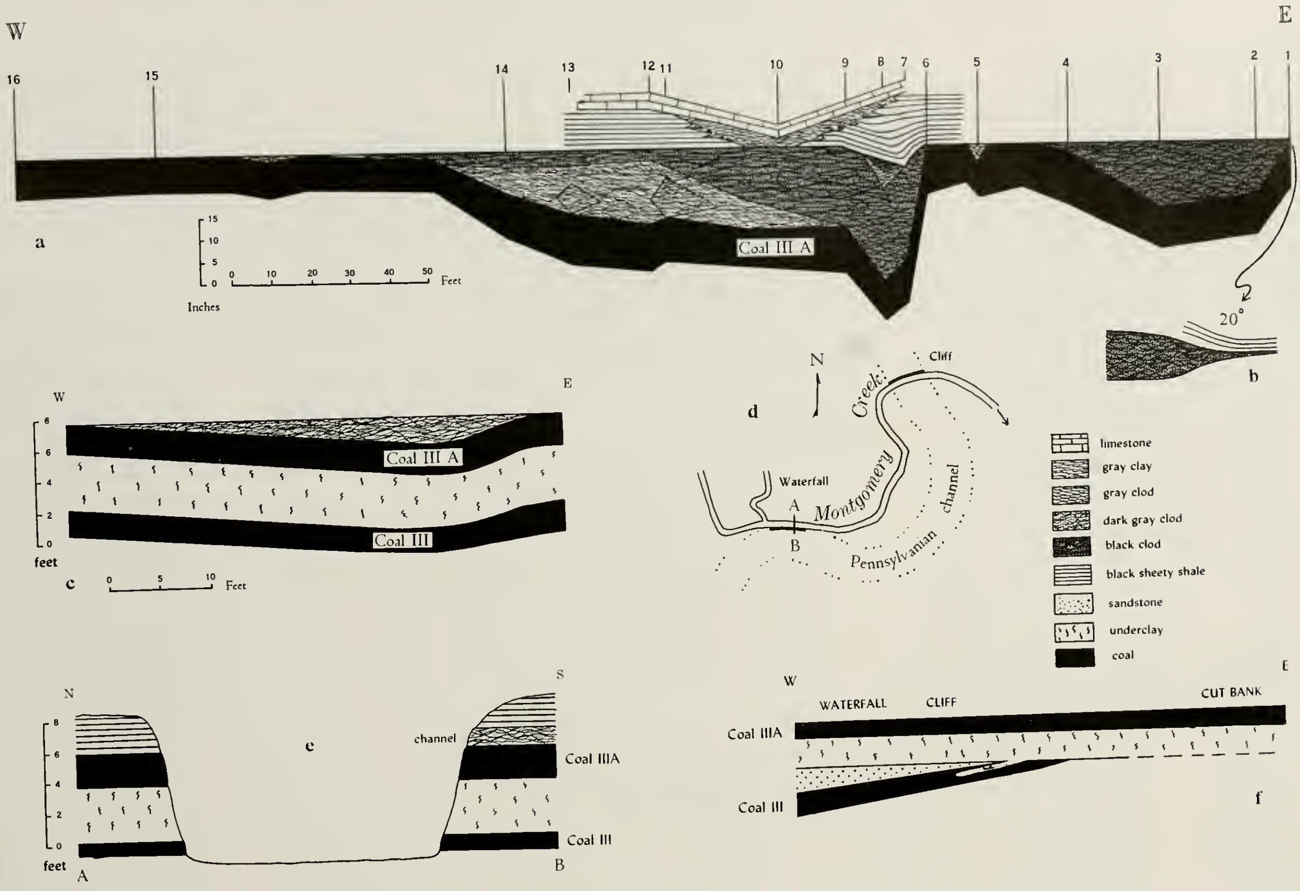

W
E
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
a
Coal III A
15
10
5
0
Inches
0 10 20 30 40 50 Feet
20°
b
W
E
Coal III A
Coal III
8
6
4
2
0
feet
c
0 5 10 Feet
d
N
Cliff
Creek
Waterfall
A
B
Montgomery
channel
Pennsylvanian
limestone
gray clay
gray clod
dark gray clod
black clod
black sheety shale
sandstone
underclay
coal
N
S
8
6
4
2
0
feet
A
B
e
channel
Coal IIIA
Coal III
W
E
WATERFALL
CLIFF
CUT BANK
Coal IIIA
Coal III
f

FIG. 9. Stratigraphic details at West Montezuma and Montgomery Creek. (*a*) Section along headwall of westernmost portion of clay pit at West Montezuma, showing clod-filled channel sections. Note at point 10 the vertical continuance of the channel to the base of the Velpen limestone. (*b*) Detail of edge of easternmost channel. (*c*) Section of clod-filled channel as exposed in cliff on Montgomery Creek. Neavel's samples 3A and 3B were collected here (p. 199). (*d*) Map of cliff and waterfall area of Montgomery Creek, showing presumed course of Pennsylvanian channel. (*e*) Cross section (A–B in *d*) showing channel clod on south bank only of creek. (*f*) Interpreted erosional unconformity above Coal III on Montgomery Creek. The channel filling represented in *c* and *e* is a black clod.

the Mecca Quarry member there are exposures of a higher coal and black shale. Since there is a notable dip of the beds, and we have not mapped the structure, we have estimated the intervals from Coal III to the Lower Lodi coal and from that to the Logan Quarry coal, exposed respectively in the lower part of Montgomery Creek and in a minor gully nearby to the south.

LINTON FORMATION		
The highest exposures of this formation that we have observed are in the cliff on the left bank of Montgomery Creek, where they are inaccessible for study (see pl. 5, E). On the slope at the upper end of the cliff, however, these beds are seen to be a thin-bedded silty micaceous probably non-marine sandstone, resembling a drab shale in the weathered exposure. Plant fragments, including *Neuropteris rarinervis*, are found throughout the portion examined. It is not certain that the entire section in the cliff exposure is sandy. In the cliff there are large septarian concretions, as much as 6 feet in diameter, some of which have fallen and lie in the creek (pl. 5, B).		
Velpen limestone member		
Thin limestone (not measured)		
Drab shale		3′
Limestone, spotted brown		4″
Drab shale		2′ 6″
Limestone, medium gray crystalline with sublithographic inclusions, to brown sideritic to black shaly carbonaceous Ashley (1899, p. 372) noted cone-in-cone structure in this bed.		2″ to 6″
Shale, dark gray, hard, unevenly bedded, calcareous, with limy concretions		6″
Mecca Quarry shale member		1′ 5⅛″
The top of this member is gradational into the shale of the bottom of the Velpen limestone member. The sheety fine-bedded character of the typical Mecca Quarry lithology continues at this locality to a higher horizon than at any other locality we have seen.		
Black shale, well-bedded	2″	
Contains a great number of trails and burrows, representing the infauna that moved in with deepening of the water after deposition of the typical Mecca Quarry shale. Some bedding surfaces are generously covered with pyritized circular markings taken to represent seaweeds (p. 122); similar markings are plentiful at the West Montezuma and Arketex Ceramic localities. Holdovers of the Mecca fauna remain briefly in association with the new infauna: on a single bedding surface we saw a *Concavicaris* test, a paleoniscoid skull and a worm burrow.		
Hard black sheety shale	5″	
Probably equivalent to top of the member at Mecca Quarry.		
Softer black sheety shale	2½″	
Moderately hard black sheety shale	3½″	
Splits readily into four sheets which are in turn readily cleavable on numerous bedding planes; equivalent to level B of Mecca Quarry. Ashley (1899, p. 373) reported "fish scales" in the black shale at the cliff exposure. We saw the following fossils in the respective layers of this level:		

B1 (Soft black splintery, somewhat harder than B3)
Petrodus
Shark

B2 (Hard black sheety, the middle half particularly hard)
Earthy coprolites
Listracanthus
Concavicaris

B3 (Black soft firm flexible finely bedded)
Shark gastric residue
Petrodus (common)
Coprolites (common)

B4 (Hard black sheety; flinty in middle half)
Palaeoniscoid gastric residue
Petrodus
Listracanthus
Acanthodian

Soft gray sheety shale with limy concretions; corresponds to level C of Mecca Quarry . . . . . 3½″

Hard black shale with *Dunbarella* . . . . . ⅝″
Corresponds to level D of Mecca Quarry.

Transgression shell breccia and channel clod
Varies from 0 to 14 inches; see discussion below.

Coal IIIA . . . . . 1′ 7″
Varies in thickness and character; see discussion below and Neavel (p. 212, *infra*).

Underclay or drab clay-shale . . . . . 3′ 4″
The interval between Coals III and IIIA varies from 3 feet, 4 inches of underclay at the cliff exposure to 7 feet, 1 inch of underclay and sandstone at the waterfall. Between the cliff and the waterfall, the upper 2 inches of Coal III become sandy, and a lens of fine-grained micaceous well-bedded sandstone makes its appearance between Coal III and the underclay of Coal IIIA. As exposed at the waterfall, this interval has the following composition:

Coal IIIA	1′	5″
Underclay	3′	3″
Sandstone, coarse, gray		7″
Sandstone, gray, with very thin and irregular bedding	1′	1″
Sandstone, medium-grained, tan with even bedding		7½″
Sandstone, gray, fine-grained with thin but irregular bedding	1′	5″
Sandstone, black (equivalent to the sandy upper part of Coal III mentioned above)		1½″
Coal III	2′	9″

STAUNTON FORMATION

Coal III . . . . . 1′ 3″
See discussion below for variations in thickness.

Underclay, drab shale and sandstone
The bed of the stream below the cliff exposure, and the section exposed in the cut bank show gray shale, some of it with plant fragments, and sandstones. A continuous measurement is not possible because of the unknown structural attitude of the beds.

Lower Lodi coal

A coal, presumably the Lower Lodi, is to be seen in the creek bed about 500 yards downstream penetrated by clastic dikes of underclay forced up from beneath. In the creek bed, the coal resembles a black shale and was so reported by Ashley (1899, p. 372).

Interval

Logan Quarry shale member.. 2′

This is exposed in a minor tributary of Raccoon Creek about 700 feet south of Montgomery Creek, where it seems to have the same fauna as in the Haworth Creek section (see p. 46). Beneath it is Logan Quarry coal.

As shown in the diagram (fig. 9, *c*), the thickness of Coal IIIA remains essentially constant beneath the channel clod; measurements on the cliff face showed it to be 21¾ inches thick, including a parting ½ inch thick 11¼ inches below the top, beneath the clod, and 22 inches thick beneath the point where the clod pinched out to nothing, 22 feet away. At the waterfall the following three measurements were made:

Channel clod	5½″	7½″	1′ 2″
Coal IIIA			
Upper bench	1′ 5″	11″	11″
Parting		½″	¾″
Lower bench		4″	3½″

Coal III shows a notable variation in thickness within the sections on Montgomery Creek. At the cut bank it is not present, though this may be because of small-scale mining at some time in the past; in the cliff exposure it is relatively thin, with a large parting near the top; below the waterfall it attains a thickness of 2 feet, 9 inches where it lies beneath a wedge of sandstone. Thus, during deposition of Coal III and the overlying sandstone there may have been greater crustal sinking in the western part of this small area than in the eastern part before deposition of the mud that has since become the nearly uniformly thick underclay beneath Coal IIIA. It is possible, also, that the peat of Coal III was laid down in a topographic low which was later occupied by a stream; thus the sandstone may be a channel fill. The relation of the sandstone to Coal III and the underclay, as diagrammed in figure 9, *f*, suggests that if there is an unconformity here it is above the sandstone, which cannot therefore be correlated with the Coxville sandstone member of the Linton formation as revised by Friedman (1960). The same sandstone is encountered in the Spencer Creek section (see p. 37) and in the Indiana Geological Survey Core No. 33 (p. 34). In this core, Friedman (MS) has drawn the Linton-Staunton boundary beneath the sandstone, thus by implication correlating it with the Coxville sandstone. While there is probably no physical evidence of an unconformity either above or below the sandstone in the Montgomery Creek section, except possibly for the black sand at the bottom, we prefer to draw the formational boundary at the base of the underclay.

Measurements of thickness of Coal III and the overlying underclay:

		1	2	3	4	5	6	7
Underclay		3′ 10″	3′ (partly hidden)	3′ 7″	3′ 5¾″	3′ 4¾″	3′ 4″	3′ 3″
Coal III	coal	2¼″	3″	1′ 8″	1′ 5¼″	1′ 6¼″	1′10″	2′ 9″
	parting	4½″	6″					
	coal	8″	10″					

Columns 1–6 at the cliff exposure, 7 at the waterfall. Column 2 by Ashley (1899, p. 373); the others by the authors.

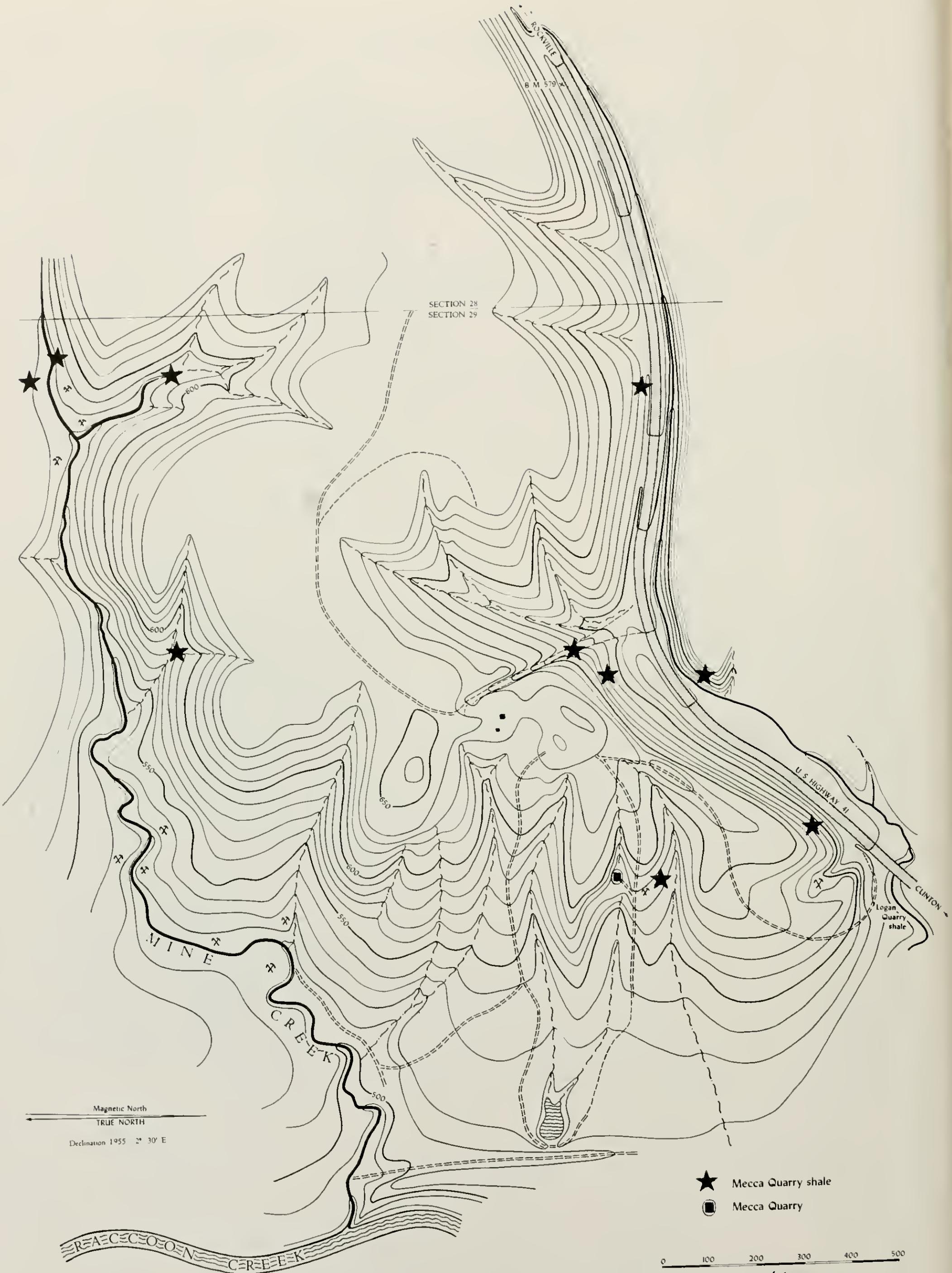

ROCKVILLE
B M 579
SECTION 28
SECTION 29
600
600
650
550
550
600
500
MINE
CREEK
RACCOON CREEK
U S HIGHWAY 41
CLINTON
Logan Quarry shale
Magnetic North
TRUE NORTH
Declination 1955 2° 30′ E
Mecca Quarry shale
Mecca Quarry
0
100
200
300
400
500
feet

FIG. 10. Map showing vicinity of Mecca Quarry and Mine Creek, from plane table traverse, 1955.

MECCA QUARRY AND HAWORTH CREEK: The portion of this section representing the Linton formation was measured in Mecca Quarry, in the lower portion along the Rockville-Clinton highway (U.S. 41) and particularly in the bed of Haworth Creek just below that highway (see map, fig. 10, for localities).

LINTON FORMATION

Velpen limestone member				at least 6′ 5″
The limy concretions and bands in this member contain sections of large crinoid stems, brachiopods, trilobites and other marine invertebrates. In the shale we have noted tubicolous worms, pelecypods, shark cartilage, chonetid brachiopods and small stems of driftwood, this assemblage probably indicating somewhat less clear water than the fauna of the limy bands and concretions. Neither fauna has been studied.				
Blue irregularly cleaving shale			1′	
Concretionary sideritic limestone			3″	
Blue irregularly cleaving shale With a line of sideritic concretions at the base.			8″	
Blue irregularly cleaving shale			3′ 8″	
Blue irregularly cleaving shale, grading downward to dark gray well-bedded shale, a transition to the Mecca Quarry shale member			10″	
Mecca Quarry shale member				1′ 10¼″
Dark gray sheety shale, breaking across the bedding in steps. Snail burrows common at the top (level A-plus)			10″	
Sheety shale with Mecca fauna (see fig. 32)			1′ 3/16″	
Level A, medium gray to black sheety shale with four prominent bedding planes setting off the following levels		3½″		
A1, medium gray	25 mm.			
A2, dark gray	20 mm.			
A3, dark gray	23 mm.			
A4, medium gray	21 mm.			
Light gray soft shale		3/16″		
Level B, medium gray to black sheety shale, with four prominent bedding planes setting off the following levels		4½″		
B1, medium gray	29 mm.			
B2, black	25 mm.			
B3, medium gray	30 mm.			
B4, black	30 mm.			
Level C, light gray, soft, sheety, with thin dark layer near top; large calcareous concretions	76 mm.	3″		
Level D, black, hard, with two moderately sharp bedding planes within it and a very clean bedding plane at the bottom	25 mm.	1″		
Transgression shell breccia: black soft carbonaceous argillaceous clay containing innumerable pyritized shells and shell fragments. A thin film, filling irregularities between flattened pyritized and coalified logs on the top surface of the coal.				

Coal IIIA			1′ 11½″
Coal		1′ 1¼″	
Clay parting		½″	
Coal		9¾″	
For description of the coal, see Neavel (p. 212 *infra*).			
Underclay, becoming drab shale beneath			5′ 2½″
Probably including the boundary of the Linton and Staunton formations.			

STAUNTON FORMATION

Coal III			1′ 6½″
Underclay, becoming drab shale beneath, partly covered			50′
This interval was not measured directly, being derived from elevation difference along the Rockville–Clinton highway near Mecca Quarry. The shale is not completely exposed in the sides of the highway and this interval may include the Lower Lodi coal.			
Logan Quarry shale member (exposed at Haworth Creek)			2′ 3⅜″
Soft gray sheety shale (level H)		4″	
Vertebrate zone (level J); black hard sheety to poorly bedded shale, with a few vertebrate fossils (palaeoniscoid scrap, acanthodian scrap)		2¾″	
Massive hard black shale	½″		
Black well-bedded but friable shale	1″		
Massive hard black shale	1″		
Black fissile shale	¼″		
Soft gray sheety shale (level K)		5½″	
Cephalopod zone (level Kb)		3″	
Black hard firm sheety shale, with *Pseudorthoceras, Dunbarella,* coiled cephalopod, gastric residues, coprolites, driftwood	2½″		
Black hard rough-bedded shale with *Dunbarella,* coiled cephalopod and *Pseudorthoceras*	½″		
Pteria zone: black hard sheety shale, finely bedded, with common *Dunbarella,* abundant *Pteria*		5½″	
Dunbarella zone: black hard sheety shale, finely bedded, lithologically indistinguishable from the above except for a somewhat irregular cleavage along the bedding. *Dunbarella* abundant as impressions, some of which are coated with a film of pyrite. At the bottom, a mat of *Dunbarella* and driftwood stems		2½″	
Myalina zone: black fairly hard somewhat irregularly cleaving humulite, with *Lingula,* gastropods, coprolites, palaeoniscoid and other fish scales, percarid crustacean, abundant *Myalina*		1⅞″	
Barren zone: black sheety humulite, hard, commonly breaking across the bedding. No fossils except for pyritized and coalified driftwood stems in the bottom half-inch		2¼″	
Logan Quarry coal (probably allochthonous)			3½″
Bright; shaly at bottom.			
Clay, dark gray, silty, poorly bedded; not a real underclay			1″
Sandstone, silty, leached, with plant fragments			5″
Sandstone, massive, micaceous			7″

Sandstone, thin-bedded, micaceous, upper part grading laterally to massive; contains burrows and stems	4′
Shale, light gray, micaceous, friable	at least 8′

MINE CREEK: The stratigraphy in this valley (NE ¼ Sec. 29, T. 15 N., R. 8 W.), less than half a mile north of Mecca Quarry, has been greatly obscured by former mining operations. The Mecca No. 2 mine was in operation during the late nineteenth century, with a rail connection through the valley to the town of Mecca. In April, 1897, this mine was abandoned (Fisher, 1898, p. 376). Later, casual "gopher-hole" mines were evidently opened on the sides of the valley. Of all these operations, the only traces now to be seen are the disturbed topography and a few of the railroad ties and bridge supports. At an elevation of about 580 feet, the Mecca Quarry shale and the underlying Coal IIIA crop out undisturbed, as this coal was deemed uneconomic to mine. Because of the topographic turmoil, it is no longer possible to measure a continuous section. The following data have been secured by a plane-table traverse (see fig. 10) and several subsequent reconnaissance visits. Though the beds, so far as they are visible, appear to be flat-lying, correlation of exposures on the traverse shows that there is actually a westward dip of 207 feet per mile in the valley, forming the eastern limb of a synclinal structure across Raccoon Valley. Thicknesses of intervals in the following section have been corrected to allow for this, and for local reversals and steepenings, so far as they could be observed.

LINTON FORMATION		
Mecca Quarry shale member		1′ ½″
The section is exposed in a small vertical bluff close to the level of the stream and partially exposed in several places in tributary valleys. The levels recognized in Mecca Quarry were clearly visible in the vertical exposure, but thicknesses of the individual beds were not measured because only weathered outcrops were available. Between the coal and the lowest black shale level (D) is a transgression shell breccia, as at Mecca Quarry.		
Coal IIIA		1′ 4½″
Coal	11″	
Parting	½″	
Coal	5″	
Underclay, with drab shale below, and covered interval.		
STAUNTON FORMATION		
Covered interval, consisting largely of light gray sandy micaceous shale with lenses and concretions of ironstone. This interval, plus the underclay and covered interval at the base of the Linton formation, including the position of Coal III		41′
Lower Lodi coal		1′ 9″
This coal occurs in at least three benches, with clay partings between, the upper bench being thick and the second rather thin. On the top surface of the coal are bark impressions; the bottom is rather bright. Where exposed in the creek bed, the coal is intruded by clastic dikes of underclay, forced up from beneath.		
Underclay, dark to light gray, blending to drab beneath.		
Drab shale, including the underclay above		at least 9′
Within this shale is a lens of sandstone, as much as 3 feet thick where exposed in the creek bed, and pinching out to nothing down-		

stream (to the west). The sandstone is heavy-bedded, coarse-grained, arkosic, with trail marks on the bedding surfaces. Where exposed, it dips downstream. Above the sandstone, the shale is light-colored; beneath, it is fairly dark. Lateral to the sandstone lens, 4 feet of light shale lie on 5 feet of dark shale.		
Logan Quarry limestone member		1′ 5″
Dark gray, muddy, unevenly bedded limestone, with corals, large crinoid columnals, brachiopods, gastropods	10″	
Dark gray fissile shale with marine fossils, corresponding to level E of Logan Quarry	7″	
Logan Quarry shale member		1′ 6½″
Black sheety shale, hard	2″	
Gray sheety shale, soft	4″	
Black sheety shale, hard, with large "niggerhead" concretions	5″	
Gray sheety shale, soft	7″	
Black sheety shale, hard	½″	
Logan Quarry coal		5″
Underclay with drab shale		at least 6′
Holland limestone member		8″
Fine-grained, dense, light brown limestone, with brachiopods.		
Holland black shale member		7′
Light gray shale	4″	
Black fissile shale	1′ 4″	
Heavy-bedded black shale	1′ 8″	
Containing many fossils (coprolites, *Petrodus*, *Listracanthus*, etc.).		
Gray fissile shale	3′ 8″	
Drab shale		12′ 6″
Black fissile shale		2″
(Probably the position of Coal IIA.)		
Light gray fissile shale		1′ 6″
Containing large flat irregular concretions and carbonized plant remains.		

DEE HOLLOW: The first major tributary valley north of Mecca, crossing the midpoint of the east edge of Section 19, may be denoted Dee Hollow (see map, fig. 7). The lower course of the stream bears abundant evidence of the industry that once flourished here. A brick and tile plant was built in this hollow in the summer of 1895 by the Dee Sewer Pipe Company of Chicago (Blatchley, 1896, p. 56) and was expanded in 1904 by the erection of an additional plant by the successor, Wm. E. Dee Clay and Manufacturing Company, the two plants together forming at that time the largest clay industry in Indiana (Blatchley, 1905, p. 115). The clay pit just south of the hollow, and the foundations of the factories are now overgrown with hardwood forest, but upstream the floor and sides of the valley exhibit a good section of the lower Linton and upper Staunton formations.

LINTON FORMATION

Velpen limestone member		at least 4′ 7″
Both the limestones and the shales in this member contain numerous marine invertebrates.		
Limestone	3″	
Because of regular vertical jointing, this bed resembles a line of bricks in vertical outcrop.		

Shale, light gray, unevenly bedded .... 2′ 10″
Limestone, concretionary .... 4″
Shale .... 1′ 2″
Dark gray clay-shale with uneven to even bedding; small limy concretions.

Mecca Quarry shale member .... 1′ 9″
Black sheety shale, fairly firm, highly cleavable on bedding planes (level A with A-plus) .... 5″
Transition from firm black to soft gray shale (level A4?) 1″
Soft gray sheety shale .... 3″
Black sheety shale; hard below, top inch soft (level B) .... 4½″
Soft gray sheety shale (level C) .... 6″
With large limy concretions 6 to 8 feet on centers; a hard dark band 4¼ to 4½ inches from the bottom.
Hard black shale (level D) with abundant *Dunbarella* ...... 1½″
Soft black channel clod with abundant marine invertebrates .... 0 to 1′
Toward the bottom the clod is light gray where fresh. Lateral to the channel, it is represented by a pyritic transgression shell breccia of irregular thickness.

Coal IIIA .... 1′ 7″ to 2′ 4″
Coal .... 9¾″..1′ 7″
Parting .... 1¼″.... 1″
Coal .... 8″...... 8″

Underclay .... about 6′

STAUNTON FORMATION
Coal III .... 7″

OKLAHOMA HOLLOW: This classic section was first reported by Hobbs (1872, pp. 345–347), exposures here forming a major basis for his general section of the rocks of central Parke County. It was remeasured, with varying results, by Blatchley (1896, p. 53), by Ashley (1899, pp. 360–361) and again by Blatchley (1905, pp. 110–111), their three sections being in fairly good agreement in the portion from the Holland Coal up to Coal IIIA. On our visit in 1955, we found some parts of the section covered, but we arrived at a measurement that closely agrees with Ashley's. Early in this century, the Mecca No. 3 mine was being worked in Oklahoma Hollow. Although the mine structures and access facilities are now long gone, disturbance of the topography remains, including an open shaft nearly full of water.

STAUNTON FORMATION
Gray shale .... 20′ 7″
Including at the bottom 1 foot 3 inches of dark gray (but not black) fissile shale.
Lower Lodi Coal .... 1′
We noted variation in thickness from 10½ inches to 2 feet 7 inches, perhaps because of duplication on a small slump fault; Ashley measured 1 foot.
Underclay, becoming drab shale below .... 9′ 2″
Sandstone .... 1′ 6″
Ashley reported it as 1 to 2 feet; we did not see a measurable exposure.

Gray shale	4′	
Covered interval	about 3′	
Includes, according to Ashley's section, the Logan Quarry limestone (1 foot to 1 foot 10 inches) with 1 foot of black "fissile" shale beneath.		
Logan Quarry shale member		11″
Black sheety shale; in the weathered exposure, we did not note the distinction between levels.		
Logan Quarry coal	1′	
Underclay	1′	6″
Measurement from Ashley; it was poorly exposed in 1955.		
Sandstone	3′	
Gray-drab shale and covered interval	4′	
Holland limestone member		6″
Holland black shale member, thinly bedded and soft above, sheety below. Ashley observed the hard sheety shale above and the softer shale beneath	4′	
Gray shale	1′	6″
Measurement from Ashley.		
Underclay, blue	2′	
Limestone, with sparse crinoid stems		6″
Limestone, sandy		10″
These limestones, like the similarly placed limestone at Dosdange Creek, may mark the position of Coal IIA, both coal and limestone representing a period of tectonic quiet.		

Collings Creeks: The following is a composite of three sections exposed in creek beds on and near the property of Ferguson Lumber Company (SW ¼ Sec. 17, T. 15 N., R. 8 W.), about a mile and a quarter north of Mecca (see map, fig. 11). This composite section includes the southernmost observed occurrence of the Mecca fauna in the Holland black shales, as well as an occurrence of this fauna in the Logan Quarry shales.

Section measured on Borden Creek:

LINTON FORMATION

Shale, drab, unevenly bedded.
A few feet exposed beneath Pleistocene cover.

STAUNTON FORMATION

Coal III	1′	2½″
Underclay	about 15′	
Dark plastic clay at top, grading down to light gray shale.		
Shale	about 3′	
Dark gray unevenly bedded clay-shale.		
Shale, black		4″
Thick-bedded but not sheety. Position of Lower Lodi coal?		

Section measured on South Collings Creek:

Interval	5′	6″
Derived from difference of topographic elevation.		
Sandstone	at least 4′	
A true channel sandstone, conglomeratic at the base, truncating the bedding of the subjacent shale, into which		

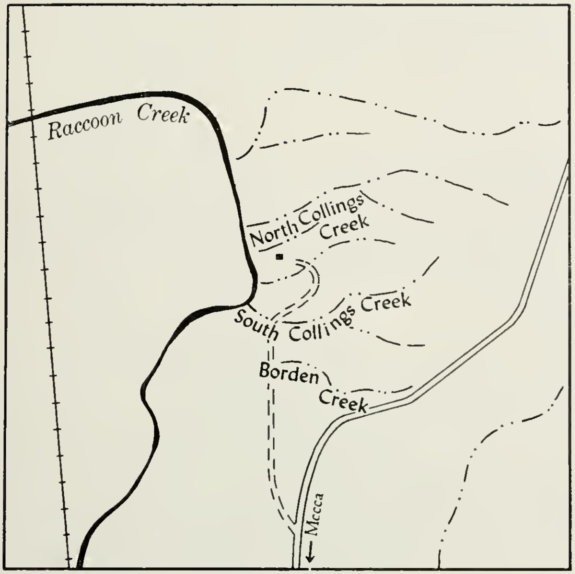

Raccoon Creek
North Collings Creek
South Collings Creek
Borden Creek
Mecca

FIG. 11. Map of Collings Creek area.
Scale: 5 inches=1 mile.

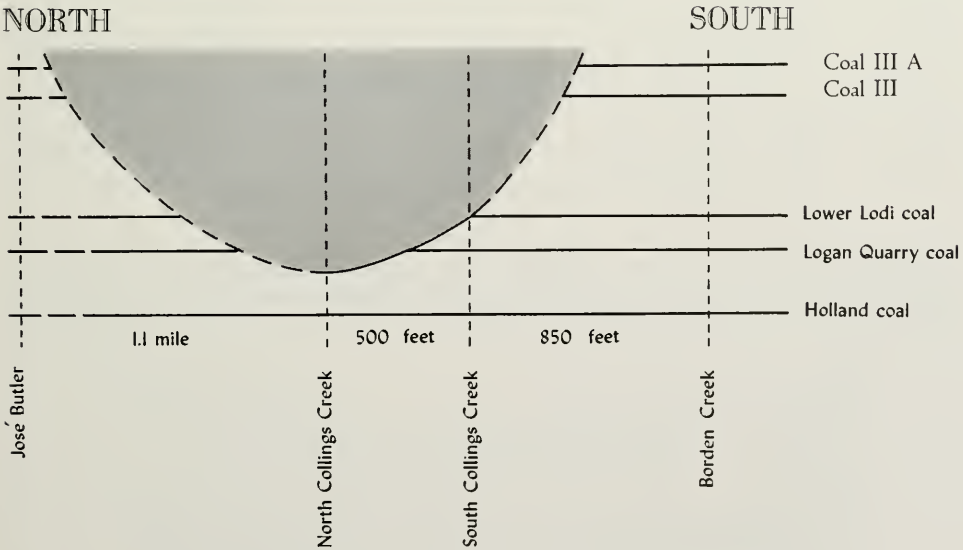

NORTH
SOUTH
Coal III A
Coal III
Lower Lodi coal
Logan Quarry coal
Holland coal
1.1 mile
500 feet
850 feet
José Butler
North Collings Creek
South Collings Creek
Borden Creek

FIG. 12. Section of sandstone-filled channel in Collings Creek area.

it was cut. This may be a part of the same drainage system as Friedman's (1960, pp. 21–23) Rosedale channel. In North Collings Creek, the base of the sandstone cuts at least 7 feet below the Logan Quarry coal member (see fig. 12).

Drab shale		9′	
Logan Quarry limestone		1′	1½″
Dark gray, muddy, fossiliferous limestone	3½″		
Gray-blue shale (level E)	10″		
Logan Quarry shale member		1′	6¾″
Soft black sheety shale (level F)	4½″		
Hard black massive to sheety shale (level G); *Edestus*	1¾″		
Soft black sheety shale (level H)	3″		
Very hard black massive shale (level J)	2½″		
Soft gray sheety shale (level K)	5″		
Hard black shale (level Kb)	¾″		
Dunbarella, *Myalina*, goniatite.			
Hard, pyritic humulite	0 to 1¼″		
Logan Quarry coal, probably autochthonous		1′	5″
Underclay to shale		17′	7″
Black on top, gray beneath, grading down to gray-drab shale (partly covered).			
Holland limestone member			7″
Tan, sublithographic, conchoidally fracturing, fossiliferous.			
Covered		1′	1¾″
Holland black shale member		4′	2¼″
Dark gray soft sheety shale	2½″		
Black firm sheety shale	3½″		
Gray soft to hard shale	3½″		
Black sheety very firm shale	3½″		
Gray soft sheety shale	4½″		
Black sheety shale	6″		
Acanthodian specimen; a shark tail from the float was probably also from this level.			
Soft gray sheety shale	6″		
Hard firm black shale	1¾″		
Black unevenly bedded shale	8″		
Dark gray to black well-bedded shale	11″		
Underclay and covered			

Section measured on North Collings Creek. This section overlaps the one measured on South Collings Creek, and is not to be read as continuous with it; see correlation diagram (pl. 55).

STAUNTON FORMATION

Sandstone	16′	
Basal three feet massive; bedded above.		
Gray shale	4′	8″
Sandstone	2′	
Covered interval, with gray shale at top and bottom	16′	9″
Holland limestone member		5″
As on South Collings Creek.		
Gray shale	3′	
Holland black shale member	2′	1½″
Black sheety and gray shales, alternating.		

Gray shale	6′ 3½″
Covered interval	5′ 7″
Sandstone	7½″
Gray shale with concretions	at least 1′

Armiesburg Vicinity: The column at Armiesburg Bridge over Raccoon Creek (east side of Sec. 12, T. 15 N., R. 9 W.) has been recorded by Ashley (1899, p. 366). We saw less of the section exposed in 1960 than he saw, and give here only our measurement of the Mecca Quarry shale and Coal IIIA. Coal III, which was five feet thick at the old José Butler place a mile to the east (op. cit., p. 365), is not present here.

LINTON FORMATION

Mecca Quarry shale member			1′ 9″
Levels A and B, with some A-plus		1′ 1½″	
Soft black sheety to fissile shale	6″		
Hard black shale	1¼″		
Soft black fissile shale	4½″		
Hard black sheety shale	1¾″		
Level C, soft gray fissile shale		5¼″	
Level D, hard black sheety shale *Listracanthus* and *Dunbarella.*		1¾″	
Transgression shell breccia Weathered to a sooty material.		½″	
Coal IIIA, with no parting			1′ 3½″
Underclay			

The exposure on the José Butler place, well described by Cox (1870, pp. 113–114), has long served as a standard section in the Raccoon Valley. By 1960, however, the outcrops had been destroyed and the topography very much disturbed by former mining activity, so that it was no longer possible to study this section in the field. All that we are able to add to the published section is that the Mecca shale fauna was present, as attested by an orodontid shark skull seen as an impression in a loose piece of black sheety shale. Such shale is reported from four horizons (Mecca Quarry, Lower Lodi, Logan Quarry, Holland); we suppose that this specimen came from one of the two lower levels.

Arabia: The Mecca Quarry shale is exposed in the hillside below Arabia Cemetery (see map, fig. 13), where it forms the roof of a "gopher-hole" mine in Coal IIIA. The thick section of drab shale beneath the coal was not measured directly.

LINTON FORMATION

Mecca Quarry shale member This measurement includes the entire member through A-plus. Level B4, a hard black sheety shale, forms the roof of the mine tunnel, spanning a width of about 5 feet.		1′ 5″
Level C: soft gray sheety shale; concretions not observed	6″	
Level D: black solid shale with *Dunbarella* and *Petrodus*	1″	
Soft gray sheety shale This appears to take the place of the usual transgression shell breccia, which is absent at this locality.	½″	
Coal IIIA		1′ 7½″

Coal	1′ 2¾″
Parting	¼″
Coal	4½″

Underclay, becoming drab shale beneath

STAUNTON FORMATION

Drab shale, including the underclay above

A thickness of 39 feet of this unit was seen in the hillside below the mine opening. The bottom of the unit is exposed near the bridge 500 yards north of the cemetery, where 3 feet 3 inches of drab shale was measured above the Lower Lodi coal. Since the elevation of Coal IIIA is about 590 feet and that of the Lower Lodi coal is 530 feet, the entire interval may be on the

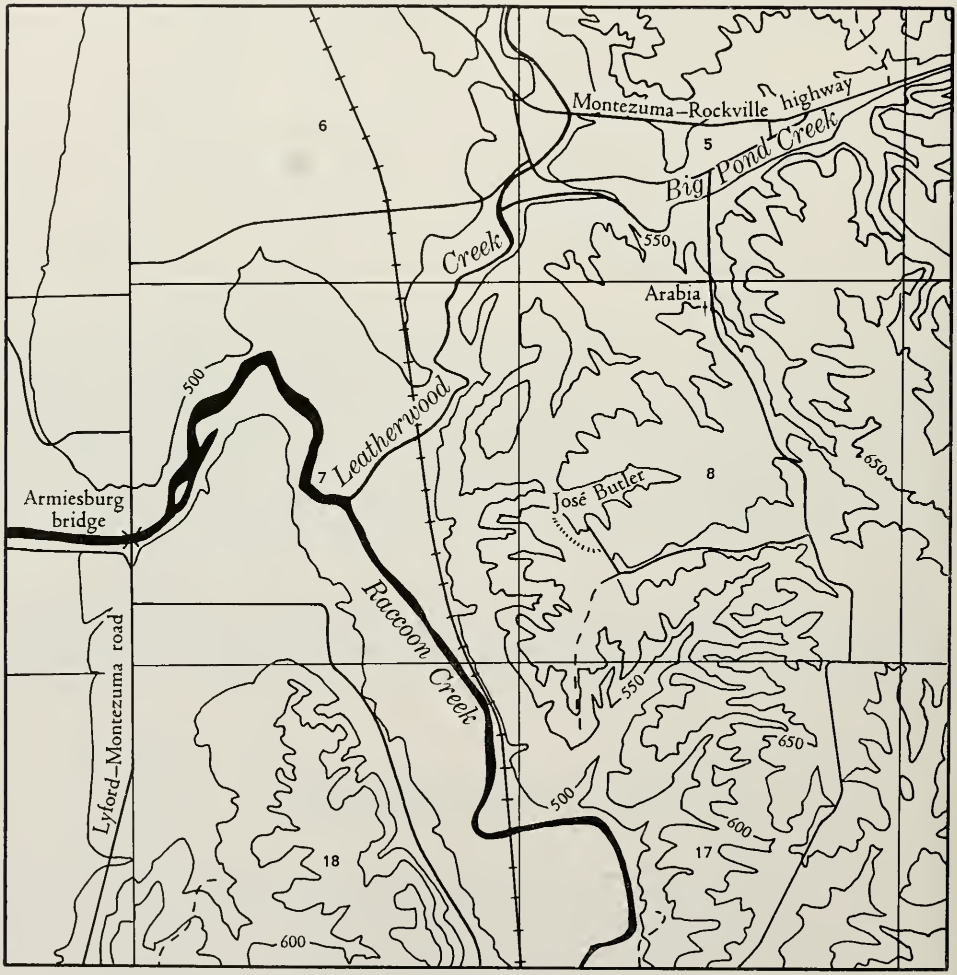

Montezuma–Rockville highway
Big Pond Creek
Creek
6
5
550
Arabia
500
Leatherwood
7
8
650
José Butler
Armiesburg bridge
Raccoon Creek
Lyford–Montezuma road
550
650
500
600
18
17
600

FIG. 13. Map showing vicinity of Armiesburg and Arabia. Scale: 2⅝ inches = 1 mile.

order of 60 feet, a thickness that might be profoundly modified by the existence of even a slight dip in the beds.		
Lower Lodi coal	2′	1″
A good solid coal, mostly dull; has been casually mined for domestic consumption.		
Underclay	2′	5″
The upper four inches moderately dark gray, the rest light beige, with a sharp basal contact.		
Shale, medium dark gray, friable, with small sideritic concretions; the section below this is concealed beneath the surface	5′	6″

Big Pond Creek: The name that we use for this tributary of Leatherwood Creek is the name appearing on the Parke County Highway Department map. On the subsequently issued United States Geological Survey Montezuma topographic quadrangle, the creek is labeled Rocky Run, a name also used by Hobbs in 1872. Although this is no doubt the preferred name, it is so similar to that of Rock Run, a tributary entering Raccoon Creek near Coxville, that we shall use the name appearing on the Highway Department map.

Where the road to Coloma leaves the Montezuma-Rockville highway (U.S. 36) and continues up the valley of Big Pond Creek (NW ¼ Sec. 4), a high cut-bank exposes the upper part of the section given below. From the foot of that bank, our section runs in the bed of the stream about to the line between sections 4 and 5 (map, fig. 14).

This exposure was known to Barnabas Hobbs, and some of his observations are worth reviewing. He reports (1872, p. 360) that ". . . in Section 4, on Soloman [*sic*] Woodard's place, L and M crop out in a ravine, where they are mined to good advantage. The upper seam measures about 20 inches, and is separated from the seam below by eight feet of fire clay." On the accompanying map, Woodard's place is located in the southwest quarter of section 33 (T. 16 N., R. 8 W.); Ashley, however, locates Woodard in the northwest quarter of section 4 (T. 15 N., R. 8 W.). In either location the elevation on the ravine in question cannot be lower than about 580 feet, an elevation appropriate to Coals IIIA and III. In our exposure in the cut-bank, sandstone occupies this elevation and both IIIA and III are missing.

"On the opposite side of the valley of Rocky Run," Hobbs continues, moving across to where we have our section, "these seams are inferior in quality. A carboniferous slate is found accompanying the lower vein at this place, which is sufficiently solid and durable to make good flagging." In making the leap across the valley, Hobbs evidently tangled his correlation, since the "lower vein," accompanied by the "carboniferous slate," is now at an elevation of 535 feet. This is clearly the Logan Quarry shale. A local resident told us that the heavy slaty black shale of this member can be used for roof tiles, and indeed it is durable, joint blocks of it remaining unweathered in the stream for years.

Hobbs goes on to trace his coals up the valley of Leatherwood Creek toward Bloomingdale; in this enterprise he is considering the Logan Quarry beds (see our section, p. 63, at the Bryant locality on Leatherwood Creek).

LINTON FORMATION?

Coxville sandstone member?

Sandstone, massive	8′	
Shale, light gray, grading upward to shaly sandstone	12′	11″
Sandstone	1′	6″

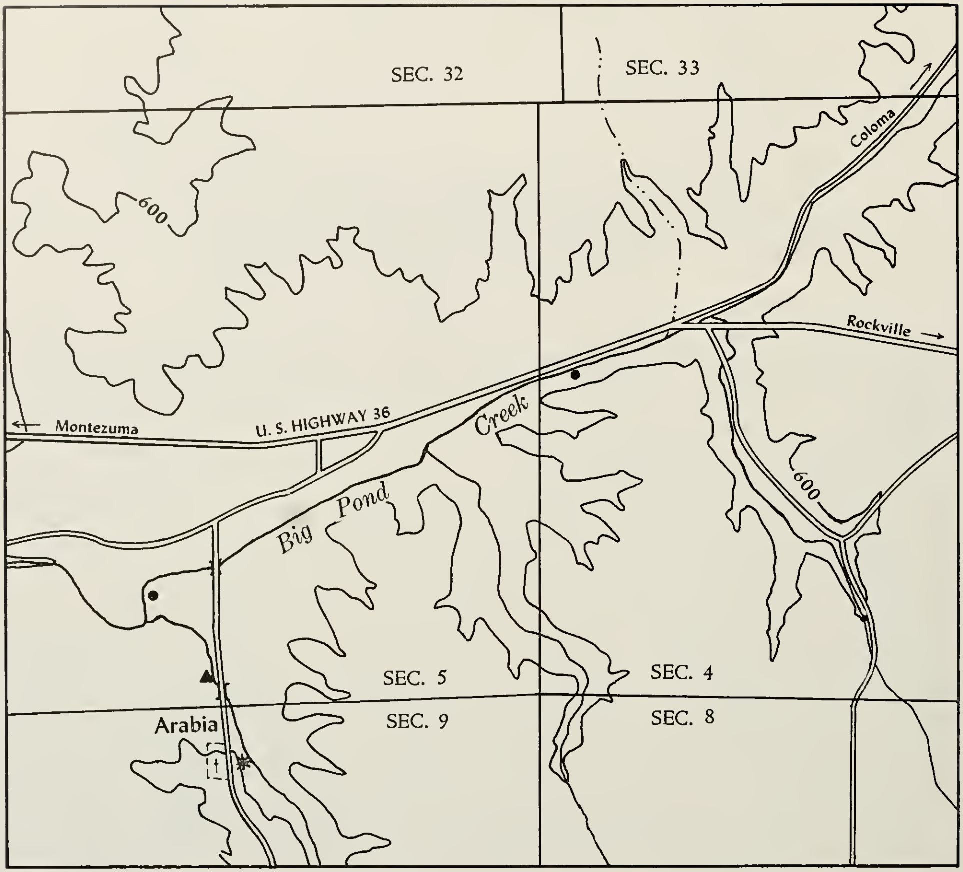

SEC. 32
SEC. 33
Coloma
600
Rockville
Montezuma
U. S. HIGHWAY 36
Creek
Pond
Big
600
SEC. 5
SEC. 4
SEC. 9
SEC. 8
Arabia

Fig. 14. Map of Big Pond Creek area. Black dots indicate outcrops of Logan Quarry shale; triangle marks outcrop of Lower Lodi coal; asterisk marks exposure of Mecca Quarry shale in a small drift mine at Arabia. Scale: 4¾ inches=1 mile.

STAUNTON FORMATION

Shale, light gray . . . . 20′ 4″

—Position of Lower Lodi coal(?)—

(Ashley, 1899, p. 376: "Coals Vb and Va are exposed every little ways down the creek, coal Va seldom showing any coal . . .")

This coal was present a mile and a half to the south at the old José Butler locality, with a thin black shale on top of it (see Cox, 1870, p. 114).

Shale, dark gray, friable . . . . 10′ 6″

Near the bottom are two 2-inch bands of concretionary sideritic limestone.

Logan Quarry limestone member . . . . 1′ 5¼″

Black, bituminous, unevenly bedded limestone with crinoid stems, brachiopods, *Lophophyllidium* . . . . 4¼″

Shale, black friable to dark blue irregularly bedded (level E)	1′ 1″	
Logan Quarry shale member		3′ 5¼″
Shale, soft gray sheety (level F)	4½″	
Shale, black hard sheety (level G)	3″	
Shale, soft gray sheety (level H)	4″	
Shale, hard black sheety in two benches (level J)	4¼″	
Shale, soft gray sheety to fissile, with concretions (level K)	5″	
Shale, hard black moderately well-bedded (level Kb)	3½″	
Shale, hard black, breaking conchoidally across bedding; *Dunbarella* numerous in bottom	9″	
Shale, soft black sheety	5″	
Shale or humulite, hard sheety	1″	
Shale or humulite, soft fissile	2″	
Logan Quarry coal, allochthonous		3½″ to 11″
Dark gray to black shaly muck, with irregular fracture, grading to coal at the top; bedded; with calcareous levels		1′
Underclay, blue		

The Logan Quarry coal at this locality is gradational with the units above and below; the unit beneath the coal bears some resemblance to a channel clod but seems to lack fossils; it is probably to be correlated with Level M at Logan Quarry, which is believed to represent a brief marine incursion preceding the laying down of the coal. In the bed of Big Pond Creek, continuous with the section beginning at the cut-bank, the coal, properly speaking, is 3½ to 4 inches thick; downstream, nearly to the bridge where the road from Arabia Cemetery crosses Big Pond Creek (see map, fig. 13), is an isolated exposure of the Logan Quarry shale and coal members. At that place, the coal is 11 inches thick and sharply separated from the beds above and below; the black shaly muck does not there intervene between the coal and the underclay. Presumably, then, the muck is a lateral equivalent of the lower part of the coal and may represent coal that has been eroded and locally redeposited during the time of peat formation. For comparison with the section given above, the section at the isolated exposure with the intact coal is as follows:

Logan Quarry limestone member		1′ 5½″
Limestone	4½″	
Shale, black friable	1′ 1″	
Logan Quarry shale member		3′ 3″

Shale, black hard sheety.

This is exceptionally fossiliferous, containing abundant *Dunbarella* and occasional *Pteria* in the following sequence of beds:

Even-bedded; many *Dunbarella* impressions.

Irregularly bedded; coquina of *Dunbarella* preserved as thick calcite fillings of the impressions, each calcite filling being as much as 3 millimeters thick, the bedding of the black shale bending around the calcite bodies (pl. 24, A).

Even-bedded; many *Dunbarella* impressions; pyritized *Lingula*.

Even-bedded; many *Dunbarella* preserved as thick calcite fillings of the impressions.

Irregularly bedded; few *Dunbarella;* fragments of shells of marine invertebrates.

Logan Quarry coal	11″
Underclay, containing a sandstone lens, 0 to 1 foot thick, about 2 feet beneath the coal.	

So far as observed, there are no vertebrate fossils in the small isolated downstream exposure. They are, indeed, relatively rare in the first exposure, though there we have seen the following elements of the typical Mecca fauna in the hard black sheety levels: sharks, articulated and as ingredients of gastric residues; acanthodians.

West Montezuma: In the clay pit operated until 1958 a short distance south and a little west of the railroad station at West Montezuma (NW ¼ Sec. 35, T. 16 N., R. 9 W.) and known as Pit 3 of the Clay City Pipe Company, the Mecca Quarry shale member is advantageously exposed. Since abandonment of the pit, the shale on the dumps has weathered away and the supply has not been renewed; before that time, we collected a great many well-preserved fossil vertebrates of the Mecca fauna in the large joint blocks of black sheety shale on the dumps; while the headwall exposure was still fresh we were able to measure vertical sections of the black shale and of marine channel deposits lying upon Coal IIIA.

The first section below is from Blatchley (1896, p. 67), with the current nomenclature of the beds introduced, measured at an exposure in a former clay pit in the gully directly west of the West Montezuma railroad station, behind the present kilns. We measured the second in a small pit that is adjacent to (north of) the main clay pit of our study and lies slightly closer to Blatchley's measured section than the rest of our exposures. The remaining sections from the headwall of the main pit are numbered according to their positions in figure 9.

Section from Blatchley:

LINTON FORMATION		
Shale, blue to drab argillaceous		25′ to 30′
Concretionary iron carbonate in two bands representing the Velpen limestone member, near the base	6″	
Mecca Quarry shale member		2′ to 3′
Shale, black fissile.		
Coal IIIA		1′
Fireclay, white siliceous		5′ to 7′
STAUNTON FORMATION		
Shale, blue and drab argillaceous		42′

Section in north pit:

LINTON FORMATION		
Mecca Quarry shale member		
Black shales (weathered)	11″	
Black hard sheety shale	1″	
Gray soft sheety shale (level C)	2¾″	
Dark at the base; contains *Petrodus,* palaeoniscoid skull, driftwood; no *Dunbarella.*		
Transgression shell breccia, pyritic	⅜″	
Coal IIIA, with no parting (upper bench)		9¼″
See Neavel (*infra,* p. 203).		

In some of the sections along the headwall of the main pit four lenticular beds of channel clod representing one or more marine channels were exposed.

Section No. 1:

This is not a measured section; it merely locates the east end of the east lens. At this place, the channel clod lens pinches down to a thin transgression shell breccia within a very short distance, so that the beds of black shale above have acquired a notable dip (see fig. 9, *a*, *b*) in rising over the lens. The coal beneath has a small dip beneath the lens.

Section No. 2; 2 meters west of Section No. 1:

Black clod lens	1′ 2″	
Coal IIIA		10½″
Underclay		

Section No. 3; 8.3 meters west of Section No. 2:

Black clod lens	1′ 5″	
Coal IIIA		11″
Underclay		

Section No. 4; 7.7 meters west of Section No. 3:

Black clod or transgression shell breccia	2″

Section No. 5; 8 meters west of Section No. 4:

Shale, dark gray, well-bedded, soft, pinching out to nothing at each end to form a lens two meters long	5¾″	
Coal IIIA		9¼″
Underclay		

Section No. 6; 6 meters west of Section No. 5:

Level D, hard black shale	¾″	
Transgression shell breccia	2″	
Coal IIIA		1′
Underclay		

Section 7; about 1.6 meters west of Section No. 6:

LINTON FORMATION

Velpen limestone member		3′ 5″
Concretionary limestone with marine fossils	4″	
Shale, light gray fissile	2′ 6″	
Concretionary limestone, hard	3″	
Shale, dark gray friable	4″	
Mecca Quarry shale member		2′ 9″
Shale, dark gray fissile	5″	
Shale, hard black sheety (vertebrates)	2″	
Shale, black fissile	3″	
Black clod with crowded *Desmoinesia*	1′ 11″	
Coal IIIA		1′ ½″
Underclay		

Section 8; about 2.2 meters west of Section No. 7:

LINTON FORMATION		
Velpen limestone member		
Concretionary limestone, hard	3″	
Mecca Quarry shale member		3′ 8″
Sooty clay	1½″	
Shale, dark gray fissile	7″	
Shale, black hard sheety (vertebrates)	3½″	
Black clod with crowded *Desmoinesia*	4″	
Gray clod, shaly, with *Desmoinesia*	4″	
Black clod, with crowded *Desmoinesia*	2′	
Coal IIIA		

Section 9; 3.2 meters west of Section No. 8:

Shale, hard black	¾″	
Black clod with crowded *Desmoinesia*	1′ 9½″	
The top part of the clod is well-bedded and contains fewer brachiopods.		
Coal IIIA		1′ ½″
Underclay		

Section 10; about 5.7 meters west of Section No. 9:

LINTON FORMATION		
Velpen limestone member (probably including higher beds).		
Shale, light gray, irregularly bedded	16′ 5″	
Contains pectinids and the following plants: *Neuropteris rarinervis* *N. scheuchzeri* *Lepidostrobophyllum majus* *Pecopteris oreopteridia* *Calamites* sp.		
Shale, dark gray	11¾″	
Contains *Mesolobus* and *Dunbarella.*		
Limestone with marine invertebrate fragments	3″	
Shale, gray with pyrite concretions	1′ 11¼″	
Contains *Dunbarella.*		
Sooty clay	2¾″	
Limestone	3½″	
Mecca Quarry shale member		2′ ¾″
Sooty clay, laterally grading to dark shale with fish fragments	2¾″	
Shale, black, poorly bedded	1′ 10″	
Equivalent to the black channel clod but with more cohesion and better bedding; contains *Desmoinesia*, but in somewhat smaller numbers than does the typical black clod. Laterally, there is a vertical division of this member into two units:		
Shale, black fissile	1′ 3¾″	
Shale, dark gray fissile	6¼″	
Coal IIIA		9½″
Underclay		

Section No. 11; 9.3 meters west of Section No. 10:

Shale, black hard.		
Black clod with *Desmoinesia;* sheety on top	5″	
Clay, gray	3″	
Clay, gray-black	11″	
Coal IIIA		

Section No. 12; about 1.6 meters west of Section No. 11:

LINTON FORMATION		
Velpen limestone member		
Limestone	3″	
Mecca Quarry shale member		2′ 7″
Shale, dark gray, fissile	9½″	
Shale, dark gray, hard, sheety	1½″	
Contains *Petrodus*, orodontid shark teeth, palaeoniscoid scales.		
Black clod	3″	
Contains crowded *Desmoinesia.*		
Gray clod	1′ 5″	
Desmoinesia less abundant than in the black clod.		
Coal IIIA		

Section No. 13; 6.4 meters west of Section No. 12:

Shale, black, hard (level D)	¾″	
Black clod	4″	
Abundant *Desmoinesia.*		
Clay, gray	5″	
Shale, gray, fissile	8″	
Coal IIIA		11½″
Clayey on top.		
Underclay		

Section No. 14; 6 meters west of Section No. 13:

Shale, black, hard (level D)	½″	
Black clod	4½″	
Abundant *Desmoinesia.*		
Clay, gray	6¾″	
Coal IIIA		1′
With pyritic concretions in the top part.		

Section No. 15; 30 meters west of Section No. 14:

Shale, black, hard		
Shale, gray, sheety (level C)	4″	
Shale, black, hard (level D)	½″	
Coal IIIA		9½″
The top ½ inch of the coal is hard fusain.		

Section No. 16; 12 meters west of Section No. 15:

Shale, black sheety	2½″	
Shale, gray sheety	1″	
Shale, hard black sheety	3¾″	
Shale, hard black sheety (level D) without *Dunbarella*	½″	

Coal IIIA	11″
The top of the coal is fusain.	
Underclay	

When we visited this locality in 1955, there were large blocks of black channel clod at the base of the headwall, containing numerous *Desmoinesia* and *Lophophyllidium.* The pit workers were familiar with this facies, and told us that it was encountered in small local areas during the stripping of the pit. When we returned in 1960, the pit had been enlarged, and exposures of the channel clod in the headwall (as given in the measurements above) were thinner than the blocks previously seen.

The channel clod in our section No. 10 extends all the way to the limestone, indicating that the channel, estuary, or bayou in which it was deposited persisted as a topographic low through all of Mecca Quarry shale time. Laterally to this point, the channel clod is succeeded by black sheety shales, as at numerous other localities. At sections 15 and 16, the top of the coal consists of a layer of fusain, which may be interpreted as indicating drying or oxidizing conditions (see Neavel, p. 207, *infra*), very probably due to its having lain above the water table when it was peat. The black sheety shale above it does not contain *Dunbarella;* if this was locally higher land, these scallops would have had an opportunity to retreat to the lower channel during the dry season (see p. 176) when the basal layer of black shale was deposited.

Thus both the large channel with its brachiopod-coral-crinoid fauna and the fusain-covered local highland fit our picture of an irregular topography on the peat swamp prior to transgression. The invading sea, entering such channels from the west or southwest, invaded the Mecca Quarry area to the east; when the water level dropped in a succeeding dry season, the water was locally ponded behind barriers such as the relatively high ground at stations 15 and 16, with the consequences detailed elsewhere (p. 222).

HIGHLAND: From the village of Highland, a minor road leads east, down the steep edge of the Wabash Valley, to the station and brick kilns at West Montezuma half a mile away, passing the abandoned Clay City Pipe Company Pit No. 3. To the west, this road descends onto the flood plain of Little Raccoon Creek at the point where an anonymous tributary also comes down. In the bed of the tributary and in the walls of its valley the Mecca Quarry shale member is seen, with the following section:

LINTON FORMATION		
Velpen limestone member and higher beds		
Gray shale		25′
Mecca Quarry shale member		1′ 2¾″
Level A: gray and black sheety shale	4¼″	
Level B: black and gray sheety shale	4″	
Level C: soft gray well-bedded shale	6″	
Level D: hard black sheety shale	½″	
Transgression shell breccia: broken shells of marine invertebrates in black mudstone; a thin film, laterally thickening to a black channel clod with crowded *Desmoinesia*, replacing the underlying coal and the overlying levels D and C.		
Coal IIIA		11½″
Coal	4½″	
Parting	½″	
Coal	6½″	
Underclay		

The Highland section is of interest because at this most seaward locality an inlet channel existed during the entire period of peat formation and for part of the time of black shale deposition. In the more landward localities farther east, the channels are few and do not replace the coal.

Bryant Locality: Hobbs (1872, p. 361) traced the coal beds northward from Big Pond Creek and reported that the "upper mine" could be followed up Leatherwood Creek, cropping out at, among other places, Bryant's farm in section 21 (T. 16 N., R. 8 W.). As we have mentioned (p. 55), Hobbs' correlations are fallible. By the "upper mine" he meant both IIIA and Lower Lodi in the Big Pond Creek area. We have seen a small exposure, which we enlarged by digging, in a gully above Leatherwood Creek at an elevation of 580 feet in the same Land Office section. In lithology and topographic position, this seems to represent the Logan Quarry shale, which Hobbs apparently predicted might be found in Leatherwood Valley.

Our section is, of course, truncated above and below so that it adds nothing to our knowledge of the succession and intervals within the Staunton formation as a whole, nor can we be certain that we are dealing with the Logan Quarry beds rather than the Lower Lodi beds. However, the ample development of the black shale and the meager amount of coal strongly suggest that this is the Logan Quarry horizon. This interpretation is borne out to some extent by the presence of a two-foot limestone, presumably the Minshall, at an elevation about 48 feet lower in a well reported by Ashley (1899, p. 352) on the Branson place in the same Land Office section.

STAUNTON FORMATION		
Logan Quarry shale member		
Shale, black, sheety, mostly hard; (level G?)	3¾″	
Shale, soft, gray In the weathered zone where we saw it, the bedding has been destroyed and the shale cuts like cheese; (level H?).	4¼″	
Shale, black, hard, moderately sheety (Level J?); contains *Petrodus* and a shark tail.	2½″	
Shale, gray, sheety, soft; (level K?) No concretions were observed in this or in the higher soft level.	6″	
Shale, dark gray, hard, not sheety; (level Kb?) Contains *Dunbarella*.	2″	
Logan Quarry coal Soft fusain.		¼″
Light gray pyritic shale, finely bedded, fissile In the weathered condition of the exposure, it was not possible to see whether this resembled the pyritic humulite facies such as is known in Garrard Quarry. It may be equivalent to the Logan Quarry level M.		2½″
Underclay, hard and shaly, with a lens or bed of fine-grained white micaceous sandstone.		

Arketex Ceramic Corporation: A group of clay pits in the southeast quarter of section 10 and the southwest quarter of section 11 (T. 16 N., R. 9 W.) is currently being operated by the Arketex Ceramic Corporation, of Brazil, Indiana. At many places in the headwalls of these pits are fresh exposures of Coal IIIA and the accompanying rocks. All the beds vary in thickness and character, so that it is difficult to select a representative stratigraphic column. Twelve sections are represented in tabular form below and amplified in the following descriptive paragraphs. We call the interval between the limestone and the coal the Mecca Quarry shale, though its upper parts may belong to the Velpen limestone member. Presumably the shale of this interval was deposited in deeper water than were its counterparts in the more typical exposures, away from the mass of *flotant* but sufficiently close to the shore to encounter a highly variable environment of deposition.

Table 3.—STRATIGRAPHIC SECTIONS IN ARKETEX CERAMIC CORPORATION CLAY PITS

	1	2	3	4	5	6	7	8	9	10	11	12
Velpen Limestone Member:												
Limestone	3	+	+	3–5	2½	3	3	5	3½	3	2½	+
Shale	21	23½	31	21	28	23	30	30	37	23½	24	30
Limestone	0–3½	¼	3	3½		3				4	2	
Mecca Quarry shale	11	8¾	7½	6	13	12¾	15	9½		8	18	11
Coal IIIA	9	7	9½	6½	9	7½	7¼	8	3	11	9	9

+ = presence of unmeasured unit. Measurements in inches.

Section 1:

Velpen limestone member	
Limestone	3″
Shale, gray, friable	1′ 9″
Limestone	0 to 3½″
Mecca Quarry shale member	
Shale, gray, fissile	2″
Shale, black, fissile	9″
Myalina	
Dunbaretla	
Productids	
Orbiculoids	
This shale is very black at the base, grading to gray at the top. At the bottom it is hard, with numerous productids; fossils occur throughout.	
Coal IIIA	9″
Underclay, full of plant fragments and roots	

Section 2:

Velpen limestone member	
Limestone	
Shale, dark gray, friable, grading up to light gray	1′ 11½″
Limestone	¼″
Mecca Quarry shale member	
Shale, hard, massive to sheety, black, pyritic in its upper part	4″

Shale, soft, light gray, fissile	2″	
Shale, soft, dark gray, fissile	2¾″	
Coal IIIA		7″
Underclay		

Section 3:

Velpen limestone member		
Limestone, concretionary.		
Shale, soft, dark gray	1′ 7″	
Limestone	3″	
Shale, soft, light gray, friable	1½″	
Mecca Quarry shale member		
Shale, hard black sheety	2″	
The upper part is pyritic, with (?)seaweeds (see p. 122); in the lower part are snail-burrows, palaeoniscoid gastric residue, *Petrodus*, *Listracanthus:* the fauna of the "A-plus" level at other localities.		
Shale, black, fairly hard, fissile	1½″	
Shale, light gray	1¾″	
Shale, black, soft, extremely friable (channel clod)	¾″	
Coal IIIA, blocky		9½″
Underclay		

Section 4:

Velpen limestone member		
Limestone	3″ to 5″	
Shale, soft, friable, grading from dark gray upward to light gray; plant fragments	2′ 9″	
Shale, roughly bedded, calcareous—almost a concretionary limestone	3½″	
Mecca Quarry shale member		
Shale, soft, gray, fissile	2½″	
Shale, hard, dark, sheety	3½″	
Coal IIIA		6½″
Underclay, blocky, with plant fragments		

In the hard dark sheety shale, a half inch above the coal, are *Petrodus* and seaweeds but no *Dunbarella*. The upper limestone is gray and shaly at the bottom with complete shells; in the upper part it is buff with shell fragments. *Neuropteris* was recognized among the plant fragments in the shale of the Velpen member.

Section 5:

Velpen limestone member		
Limestone	2½″	
Shale, soft, dark to light gray. The bottom includes the position of the lower limestone	2′ 4″	
Mecca Quarry shale member		
Shale, black, sheety, firm	4½″	
Shale, soft gray, fissile	8½″	
Coal IIIA		9″
Underclay, clayey, not blocky, contains roots		

Section 6: Close to the place where Neavel (*infra*, p. 199) took his sample of Coal IIIA.

Velpen limestone member		
Limestone, somewhat irregularly bedded	3″	
Shale, dark gray, friable, grading upward to light gray	1′ 11″	
Limestone, concretionary	3″	
Mecca Quarry shale member		
Shale, soft, gray, fissile	5″	
Shale, hard, black, sheety	5¼″	
Shale, hard, medium-gray with conchoidal fracture	2½″	
Coal IIIA		7½″
Underclay		

Section 7:

Velpen limestone member		
Limestone	3″	
Shale, blue-gray, clayey, with conchoidal fracture The bottom includes the position of the lower limestone.	2′ 6″	
Mecca Quarry shale member		
Shale, black fissile *Petrodus* Palaeoniscoid gastric residue Coprolites	1′ 3″	
Coal IIIA		7¼″

Section 8:

Velpen limestone member		
Limestone	5″	
Shale, blue-gray, clayey, with conchoidal fracture The bottom includes the position of the lower limestone.	2′ 6″	
Mecca Quarry shale member		
Shale, dark gray, rather well-bedded	8″	
Coal (very local)	½″	
Shale, hard, fissile, black	1″	
Coal IIIA		8″
Underclay		

Section 9:

Velpen limestone member		
Limestone Actually a limy clay with broken marine invertebrate shells.	3½″	
Velpen and Mecca Quarry members		
Shale, gray, friable; hard in lower part. None of it is black.	3′ 1″	
Coal IIIA		3″
Underclay, sandy, with vertical plant remains		

Section 10:

Velpen limestone member		
Limestone, with marine invertebrates	3″	
Shale, dark gray, friable	1′ 11½″	
Limestone, hard, unevenly bedded, bituminous	4″	

Mecca Quarry shale member		
Shale, soft, gray, fissile	4″	
Shale, black, sheety	4″	
Coal IIIA		11″
Underclay		

Section 11:

Sandstone (thick)		
Shale, gray, friable		3′ 1″
Velpen limestone member		
Limestone, very impure, brown	2½″	
Shale, dark gray, friable	2′	
Concretionary bed, gray, pyritic, with no fossils	2″	
Mecca Quarry shale member		
Shale, extremely soft, dark gray, friable (a non-fossiliferous channel clod?)	5″	
Shale, light gray, soft, fissile	10″	
Shale, hard, sheety	2″	
Shale, light gray, soft, fissile	1″	
Coal IIIA		9″
Underclay		

Section 12:

Velpen limestone member		
Limestone, concretionary, with marine invertebrates		
Shale, dark gray, friable, partly indurated; the bottom includes the position of the lower limestone	2′ 6″	
Mecca Quarry shale member		
Shale, black to dark gray, hard to moderately hard	4″	
Shale, soft, light gray, fissile	7″	
Coal IIIA		9″
Underclay		about 15′
Sandstone, massive		

LOGAN QUARRY: Logan Quarry, one of our major localities, was excavated for the purpose of collecting fossils on the land of P. H. Logan (fig. 15). On the first visit we measured the section of black shale exposed in the bank of a gully on the adjoining land of Kenneth Cloyd. That section (given below), though carefully measured, is not comparable, bed for bed, with the standard section measured later in the fresh rock of the quarry excavation. The apparent difference between the two sets of measurements points up very strikingly the importance of fresh unweathered outcrops in observing lithologic differences in black shales (see p. 15). For detailed correlation and paleogeographic interpretation fresh exposures are essential. The Cloyd Gully section, 250 feet from Logan Quarry, was:

Shale, black, friable (levels E, F?)	
Shale, black, sheety (levels F, G, H?)	10″
Shale, black, sheety, thinner-bedded (level J?)	2″
Shale, black, sheety (level K?)	3″
Shale, gray, soft, well-bedded (level L?)	6″
Shale, black, sheety, thin-bedded, with bands of anthraxylon (Logan Quarry coal?)	3″
Shale, black, friable (level M?)	4″
Underclay, white, with pyrite concretions	3′ 3″
Sandstone, soft, thin-bedded	

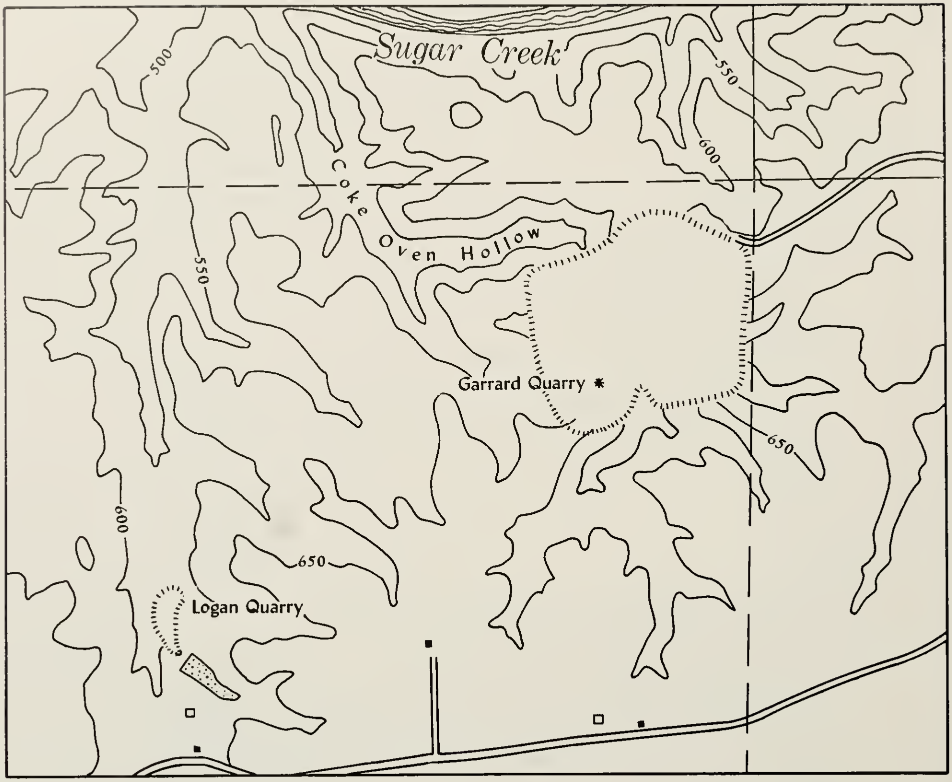


FIG. 15. Map of Logan Quarry area. Garrard Quarry, at the head of Coke Oven Hollow, is within the Cayuga Brick and Tile Corporation's clay pit. Scale: 6¼ inches= 1 mile.

Logan Quarry, as excavated, had an area of about 4000 square feet; it was 156 feet long and, at the widest, 40 feet wide. Thicknesses of individual units of the black shale varied somewhat within the bounds of the quarry, as shown by the parallel columns of measurements below, but the lithology remained constant over the whole area. The section is continued below level M with measurements in the valley wall opposite the quarry.

STAUNTON FORMATION

Logan Quarry limestone member .... 2′ 7¾″....2′ 11″

Fine-grained, argillaceous limestone, dark gray (black when wet) .... 8″.....10″

Tubicolous worm tubes (abundant)
Mesolobus striatus (common)
Lophophyllidium
Neospirifer
Ostracodes
Crinoids

Level E: dark blue-gray unevenly bedded clay shale with marine invertebrates ..1′ 11¾″..2′ 1″

Logan Quarry shale member (fig. 16)	1′ 6¹⁄₁₆″ . . . . 1′ 9⅝″
Level F: dark gray soft well-bedded somewhat sheety shale with Mecca fauna and very large coiled nautiloids	4¾″ . . . . 5½″
Level G: heavy-bedded very black hard sheety shale in two banks; has a tendency to break across the bedding. Sharks and palaeoniscoids excellently preserved; goniatites fairly common	3½″ . . . . 4″
Level H: light gray soft well-bedded to poorly bedded shale; sharks and palaeoniscoids well preserved but not common	3¼″ . . . . 3½″
Large dense calcareous concretions as much as 3 feet in diameter, are spaced 6 to 10 feet apart.	
Level J: hard black sheety shale with well-preserved fossils. A dense very black layer about ¼ inch thick somewhat above the middle (black band); a surface with scattered faunal debris and fecal matter somewhat below the middle. The principal horizon in this locality for the Mecca fauna	1⁵⁄₁₆″ . . . . 1⅜″
Level K: very similar to level H, but generally better-bedded; fossils rare, no concretions.	5″ . . . . 5¼″
Level Kb: a distinct level, but included in the measurement of level K. It is a hard black poorly bedded shale. *Dunbarella* fairly common as fragments, with rare unbroken individuals; *Microconchus* common. Thickness about 1 inch.	
Level L: pyritic humulite at base, grading upward to soft dark gray shale; *Dunbarella* abundant at top; cephalopods on top of humulite.	¼″ . . . . 2″
Logan Quarry coal: banded, with shiny anthraxylon bands separated by pyritic clay layers, allochthonous (see description and discussion by Neavel, *infra*, p. 212)	2¾″ . . . . 6″
Level M: this member is lettered in sequence with the levels of the Logan Quarry shale, though it constantly underlies the coal. Flaky dark gray mudstone, thinly laminated with gypsum. Contains *Dunbarella* and other marine invertebrates, palaeoniscoid scales and small coprolites	0″ . . . . 4″
Underclay, light gray, plastic Thinner in the Logan Quarry section than in nearby Cloyd Gully, perhaps due to a rise in the top of the underlying sandstone.	1′ 6″
Sandstone, becoming shaly toward the base Thinning to the northeast at Garrard Quarry.	3′ 7″
Shale, drab, argillaceous	4′ 5″
Holland limestone member	5½″
Shale, soft, black, irregularly bedded with a coaly bed (Holland Coal) 1 foot 3 inches below the top . . . . at least	2′ 4″

COKE OVEN HOLLOW AND GARRARD QUARRY: Coke Oven Hollow, a valley leading to Sugar Creek about three miles from the Wabash River, is a classic locality in both the stratigraphy and the history of Parke County (fig. 15). Here, in the 1830's, William G. Coffin was already making coke, exporting his product by wagon as far as Cincinnati.

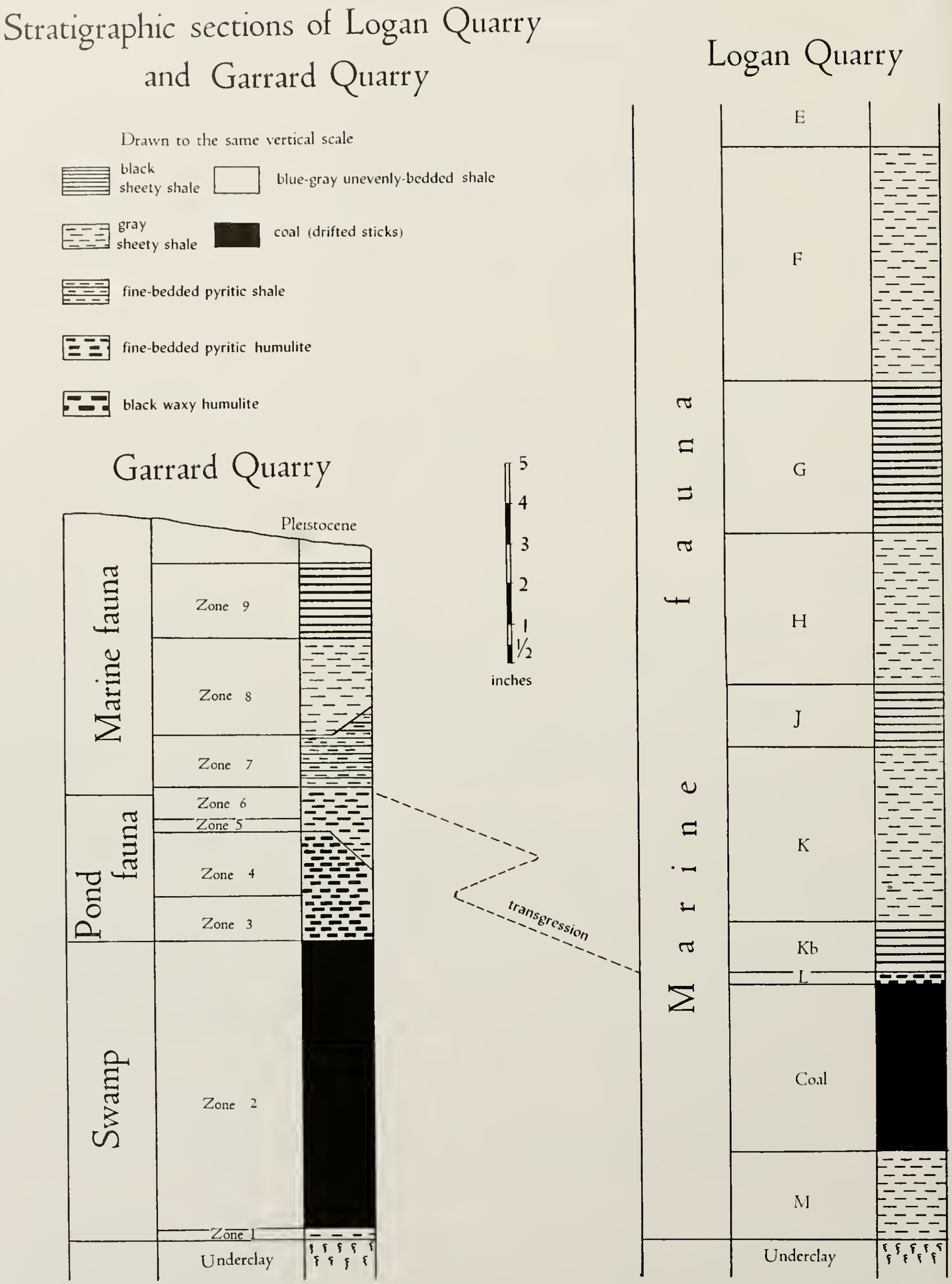

Stratigraphic sections of Logan Quarry and Garrard Quarry
Drawn to the same vertical scale
black sheety shale
blue-gray unevenly-bedded shale
gray sheety shale
coal (drifted sticks)
fine-bedded pyritic shale
fine-bedded pyritic humulite
black waxy humulite
Garrard Quarry
Pleistocene
Marine fauna
Pond fauna
Swamp
Zone 9
Zone 8
Zone 7
Zone 6
Zone 5
Zone 4
Zone 3
Zone 2
Zone 1
Underclay
5
4
3
2
1
½
inches
transgression
Logan Quarry
Marine fauna
E
F
G
H
J
K
Kb
L
Coal
M
Underclay

FIG. 16. Stratigraphic sections of Logan Quarry shale at Logan and Garrard Quarries.

Beginning with David Dale Owen in 1838, a succession of geologists visited Coke Oven Hollow and recorded stratigraphic sections. Unfortunately, there is a great deal of lateral facies change, and a section deduced from walking up the hollow is different from a section made vertically at any point; for example, the Minshall limestone crops out on both walls of the hollow at 539 feet elevation, but about a hundred yards to the south on the right wall it is replaced by a thick-bedded sandstone at the same elevation, and in an equal distance to the north it is replaced by a shaly sandstone. In consequence of the lateral variation, no two sections measured in this valley are the same, and ours is no exception.

Near the head of the hollow is the large clay pit of the Cayuga Brick and Tile Corporation, currently being actively worked. In 1960 and 1961, near the southwest corner of this pit, a few hundred square feet of black shale were exposed on a bedding surface stratigraphically equivalent to the Logan Quarry shale member, whose type locality lay about one-half mile to the southwest. The operator of the clay pit, Mr. Gerald Garrard, left the black shale for us to examine, thus providing us with by far the finest exposure we have seen of the inland fresh-water facies of the Logan Quarry shale. For convenience, we have designated this small exposure "Garrard Quarry." From it we have quarried many cubic yards of rock, containing a good representation of the fresh-water fauna. We have also thereby been enabled to zone rather closely the faunal and lithologic change from coal-swamp to pond to marine conditions as the sea with its Mecca fauna transgressed across Garrard Quarry (fig. 16).

The exposure constituting Garrard Quarry was in a small remnant, terminated on the west and north by Pleistocene deposits cutting down to lower elevations, and on the east and south by a branch of Coke Oven Hollow and earlier excavations of the clay pit. This isolated body of rock was largely removed in the continued working of the clay pit in the spring of 1962.

Our section of Garrard Quarry, made in 1960 and continued into Coke Oven Hollow in 1961, is based on continuous fresh exposures from Garrard Quarry down to ten feet beneath the *Taonurus* level below Coal II. The Minshall limestone is added from the small exposure on the right slope of Coke Oven Hollow mentioned above. Beneath the Minshall-*Taonurus* level there are at least three coal horizons to the level of Sugar Creek, including a "paper coal" similar to that reported by Neavel and Guennel (1958). However, since there are no black shales bearing the Mecca fauna, we do not include the portion of our section that lies below the Minshall.

STAUNTON FORMATION		
Logan Quarry shale member		8¾″
(Upper part removed by Pleistocene erosion.)		
Blue-gray irregularly fracturing shale with marine invertebrates (thin film seen).		
Black dense hard massive to sheety shale with cephalopods (Zone 9, equivalent to "Kb" of Logan Quarry)	1¾″	
Pseudorthoceras Coiled nautiloid (Both fairly common.)		
Gray soft finely bedded shale (Zone 8)	2¼″	
Dunbarella, pyritized, mostly fragmentary, very common; acanthodian, articulated, rare.		
Gray-green finely bedded pyritic shale (Zone 7)	1¼″	
Dunbarella, pyritized, very common, mostly unbroken.		

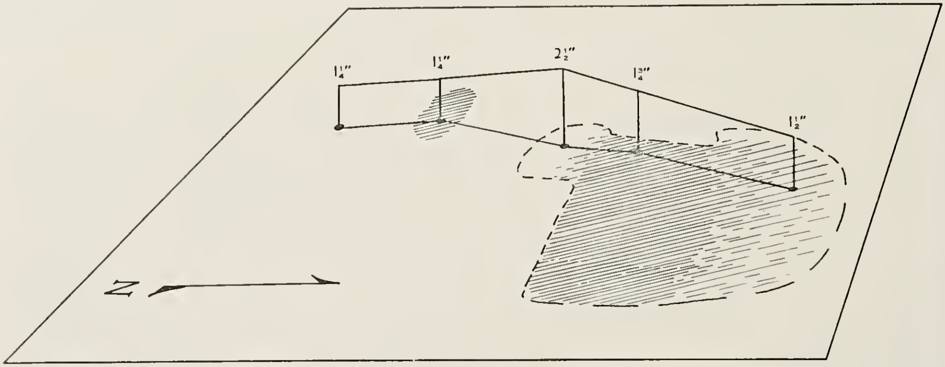


FIG. 17. Garrard Quarry; depth of shading indicates density of fossil vertebrate occurrence within limits of excavation. Superimposed section shows local variation in thickness of Zones 4 to 6.

Green finely bedded pyritic humulite (p. 113) (Zone 6)	¾"	
Myalina as specimens and as gastric residues (most common as residues); coprolites and residues abundant. All fossils except phosphatic and carbonaceous ones pyritized. *Lingula* with color pattern preserved occurs as individuals and in dense gregarious association. Palaeoniscoids fairly common as small perfect specimens. Teeth of pleuracanthid sharks and other fishes; snails; crustaceans; ferns; all well preserved. In upper quarter-inch, *Myalina* rare, *Dunbarella* and *Lingula* present.		
Green irregularly bedded pyritic humulite (Zone 5)	¼"	
Pyritized *Myalina* and *Myalina*-residues common; bones and scales of rhipidistian; teeth of pleuracanthid shark and rhipidistian; acanthodians; palaeoniscoids fairly abundant as residues and as intact specimens; snails; ferns; driftwood.		
Black waxy unevenly bedded tough humulite (Zone 4)	1½"	
Myalina shells and residues; teeth of pleuracanthids and rhipidistians; bones of large rhipidistians; snails; driftwood. *Myalina* shells may be aligned in streaks (pl. 23, B); Zones 4 and 5 vary in thickness laterally (fig. 17).		
Black waxy to coaly humulite with vertical coal-like fracture (Zone 3)	1"	
No fossils other than sticks and small debris; an acanthodian spine was seen on the top surface.		
Logan Quarry coal (Zone 2)		6¾"
Coal, very poor, consisting of bedded sticks; more compacted near bottom.		
Shale, light gray (Zone 1)		¼"
Underclay, becoming sandy shale beneath	3'	9"
Sandstone, soft white	1'	6"
Shale, light gray, irregularly bedded, with limy concretions; upper part sandy	6'	6"
Holland limestone member	3" to	7"
Tan, sublithographic, with numerous marine invertebrates; a single bed.		

Shale, dark gray, very friable		7″
Shale, black, friable		7″
Holland coal? Imperfectly bedded conchoidally fracturing black carbonaceous or coaly shale. Thin black harder levels with vertical fracture, resembling coal, at the top and in the middle. This bed plus the dark shales above and below may represent the Holland Coal and black shale of other localities.	1′	
Shale, dark gray, well-bedded, with a ½ to ¾ inch dense dark layer at the bottom		4″
Sooty material, perhaps a carbonaceous underclay		2″
Underclay, dark gray	1′	1″
Clay-shale, light gray with thin sandstone lenses; in places nearly plastic: a less-leached continuation of the underclay above	18′	
Coal IIA	1′	10″
Underclay, dark gray	1′	
Sandstone White, fine-grained, poorly bedded, soft.	5′	

BRAZIL FORMATION

Shale, light gray, friable	8′	9″
Coal II	1′	7″
Underclay Light gray, with carbonized plant remains.	2′	2″
Sandstone Light, fine-grained, weathering rusty.		4″
Clay, medium gray, plastic		3″
Clay-shale, dark gray A lens, pinching out in a short distance east and west.		5″
Shale, light gray Grading upward to the dark gray clay-shale above the lens and downward to medium gray; fissile to unbedded.	4′	6″
Sandstone Hard, thin-bedded, light, weathering rusty. *Taonurus* in top 6 inches; gradational into sandy shale beneath.	10′	3″

The units above are well exposed in a continuous section on the west headwall of the clay pit. On the basis of elevation and the presence of *Taonurus*, the following unit is correlated with the sandstone of the above section. This unit and the Minshall limestone are exposed in outcrops on the right slope of Coke Oven Hollow 1300 feet northwest of the section described above.

Sandstone Medium-grained, thick-bedded, with *Taonurus* in the top. About 30 feet along the slope, the sandstone becomes flaggy and contains plant fragments, with a massive bed 1 foot 6 inches thick at the top.	5′	10″
Shale, drab	1′	3″
Coal Dull, shaly, with fusain.	1′	3″
Underclay		

On the same slope, a few hundred feet to the north, the Minshall limestone outcrops at the same elevation as the *Taonurus*-bearing sandstone. A few hundred feet beyond, in the same direction, a shaly sandstone is to be seen at this horizon. We cannot say whether the limestone and sandstones were deposited simultaneously in a complex basin of deposition or whether the sandstone occupies channels cut around the Minshall limestone.

Minshall limestone	2′ 10″

The remarkable clay deposit near the head of Coke Oven Hollow referred to by Hobbs (1872, p. 365) as a large channel fill ("This chasm is filled with excellent fireclay . . .") is well exposed in the current stripping operation. Whether this is a north-south channel, as Hobbs suspected, seems now doubtful. At any rate the body of clay, whatever its shape, directly underlies Coal IIA and may replace Coal II.

Nettlerash Creek: Outcrops in this valley, about a mile southwest of Coke Oven Hollow (SW ¼ NE ¼, Sec. 8, T. 16 N., R. 8 W.), provide a continuous section, though not entirely exposed, of the rock sequence from the Lower Lodi coal down to and below the Minshall limestone. The name of this valley is our own.

STAUNTON FORMATION		
Lower Lodi coal		1′ 9″
Underclay		2′
Shale, drab		15′ 6″
Logan Quarry shale member		1′ 10″
Soft black sheety shale (level F)	6″	
Hard black sheety to massive shale, in two benches (G)	3½″	
Soft gray sheety shale, with large calcareous concretions (H)	4½″	
Hard black massive to sheety shale (J)	2″	
Soft black shale (K)	5″	
Hard black shale (Kb)	1″	
Logan Quarry coal		5″
With plant impressions in the base.		
Underclay		2″
Sandstone, calcareous		2′ 11″
Shale, drab, calcareous		14′
Less calcareous in lower half; concretions in upper half. A lens of sandstone, 1 foot thick, 3½ feet from the top.		
Sandstone		1′
Sandstone, flaggy		6′ 4″
—Position of Holland coal—		
Underclay and shale		11′ 9″
Coal IIA		2′ 4″
In the absence of good exposures of this coal, its thickness is scaled from elevations of the top and bottom.		
Underclay		1′ 6″
Sandstone and covered interval		21′ 7″
A few inches of sandstone were seen at the top; at the bottom is the following succession:		
Soft sandstone with flaggy bedding	1′	
Hard massive sandstone	3′	
Drab sandy shale	3′	

BRAZIL FORMATION

Shale, black, carbonaceous		1″
Probably a lateral equivalent of Coal II.		
Shale, gray, sandy		43′ 3″
This laterally replaces the Minshall limestone, of which there is an outcrop a few yards long near the mouth of the creek. The limestone is 4 feet thick, its top being 5½ feet beneath the thin black carbonaceous shale at the top of the Brazil formation.		
Shale, gray, sandy	5′ 6″	
Minshall limestone	4′	
Shale, gray, sandy.		

Dosdange Creek: Dosdange Creek, near the north edge of the U.S.G.S. Montezuma Quadrangle, rises in section 34 (T. 17 N., R. 8 W.), in which section the shales and limestones of the upper part of the following profile are exposed, and then runs between sandstone cliffs through parts of sections 5 and 4 (T. 16 N., R. 8 W.) to enter Sugar Creek about half a mile below the mouth of Coke Oven Hollow (see map, fig. 1). The name is of our own devising, since the stream is without a locally used name.

Hobbs (1872, p. 364) reported that on the Josiah Campbell place, probably this locality, ". . . a two and a three-feet seam [of coal] crop out . . . roofed by a two or three feet seam of limestone." Hobbs "was unable to find an exposure that would indicate its quality or the palaeontological character of the limestone roof." Ashley (1899, p. 358) repeated this interesting rumor, but he likewise did not see the thick coals and limestone.

The Holland coal, not roofed by limestone, is actually 1½ feet thick here and has been locally mined on a very small scale, while some 9 feet beneath it is a 3-foot limestone, which we interpret as representing an offshore facies corresponding to Coal IIA. As is usual in the stream-valley exposures in Parke County, there is no continuous section; outcrops of parts of the column must be combined into a complete column on the basis of relative elevation, with regard to dip and lensing. Two profiles of the Logan Quarry shale were measured here, as shown in figure 18. The first profile below was measured in the main valley of Dosdange Creek; the second, which is here made continuous with the stratigraphic section derived from a rod-and-level traverse down to the Sugar Creek flood plain, was measured in a branch near the township line, where the Logan Quarry shale forms a small waterfall.

STAUNTON FORMATION

Logan Quarry limestone member (not measured).		
Logan Quarry shale member		1′ 9¾″
Light gray to dark gray well-bedded soft shale (level F)	4″	
Hard black sheety to massive shale in two banks, the upper bank becoming fissile on weathering (level G)	4″	
Light gray to medium gray well-bedded soft shale (level H)	4″	
Hard black massive shale (level J)	1¼″	
Medium gray well-bedded soft shale (level K)	5″	
Black sheety shale (level Kb)	½″	
Dark pyritic shale or humulite with pyrite concretions (level L)	3″	
Logan Quarry coal, probably allochthonous		5″

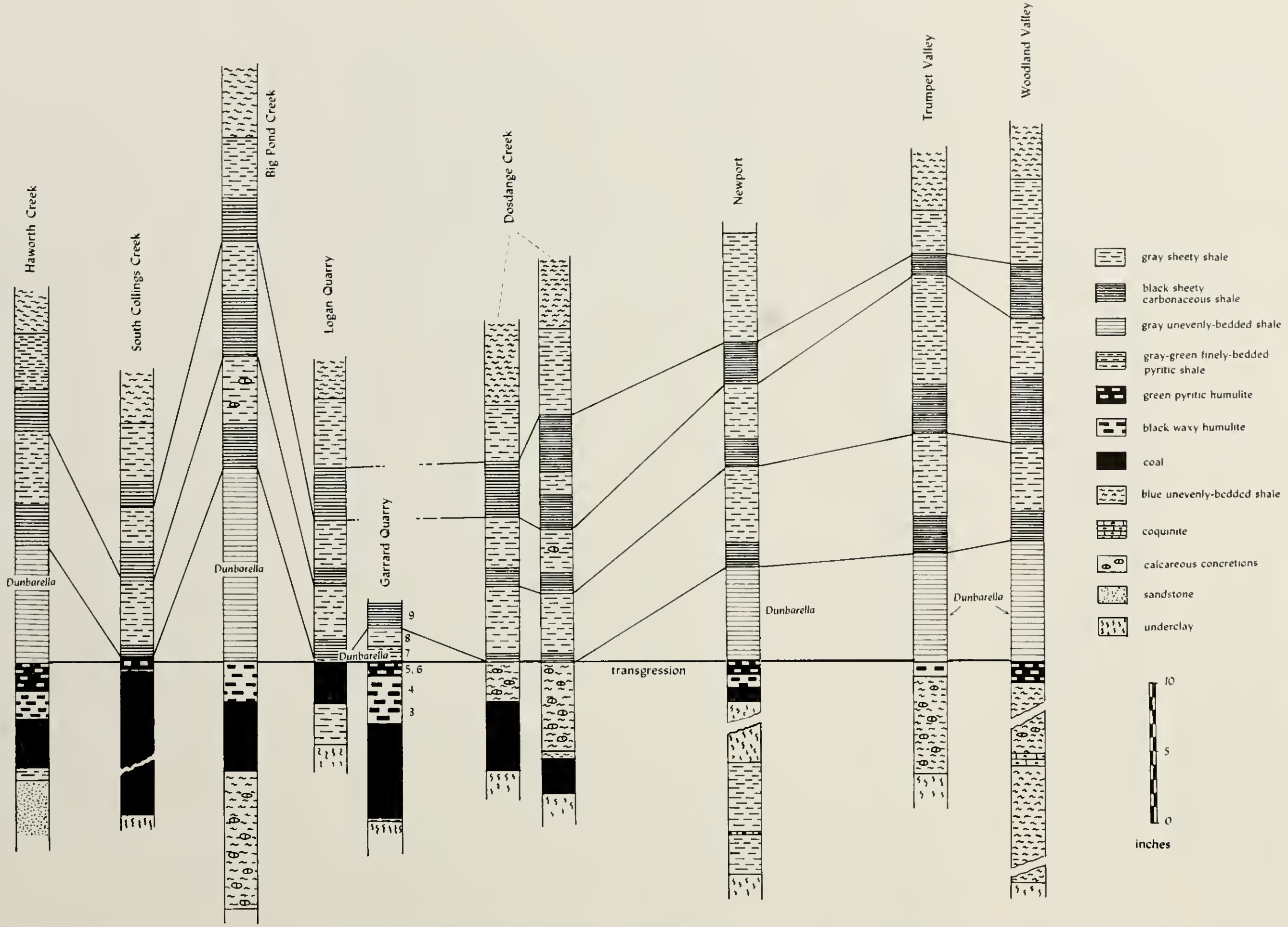

Haworth Creek
South Collings Creek
Big Pond Creek
Logan Quarry
Garrard Quarry
Dosdange Creek
Newport
Trumpet Valley
Woodland Valley
Dunbarella
Dunbarella
Dunbarella
Dunbarella
Dunbarella
9
8
7
5, 6
4
3
transgression
gray sheety shale
black sheety carbonaceous shale
gray unevenly-bedded shale
gray-green finely-bedded pyritic shale
green pyritic humulite
black waxy humulite
coal
blue unevenly-bedded shale
coquinite
calcareous concretions
sandstone
underclay
10
5
0
inches

FIG. 18. Profiles of Logan Quarry shale from Haworth Creek (south) to Woodland Valley (north). Horizontal transgression line connects nearly simultaneous marine advances across the various sections.

The second exposure, at the waterfall, is somewhat better than that in the main valley, but both are weathered:

Channel sandstone, conglomeratic at the base, with plant fragments.			
Logan Quarry limestone member			
Blue-gray unevenly bedded clay-shale (level E)		8″	
Logan Quarry shale member			2′ 7⅛″
Soft black sheety shale with worm trails		6″	
Closely similar to the A-plus level of the Mecca Quarry shale (level F).			
Black and gray sheety shale (level G)		8½″	
Hard black sheety shale	4″		
Soft gray sheety shale	2″		
Hard black sheety shale	2½″		
Soft gray sheety shale with large concretions (level H)		3¼″	
Hard black massive to sheety shale (level J)		1¼″	
Very similar to this level at the type locality but somewhat more splintery in its fracture; lacks the dense black band of the Logan Quarry J. Contains acanthodian scales, palaeoniscoid scales, conodonts, sponges, "seaweeds."			
Soft gray sheety shale (level K)		4¼″	
With shark cartilage.			
Moderately hard black shale, continuous with the above (level Kb)		½″	
Shark tooth, coprolite.			
Soft light blue-gray micaceous clay-shale with irregular fracture (level L)		7⅜″	
Thin films of matted stems at the bottom and other levels within it. Sparsely fossiliferous: plant fibers and fragments, fusain, blobs and stringers of anthraxylon, fish scales and bones. Pyritic nodules ¾ inch above the bottom at the waterfall. Directly on the coal, soft black shale. A few hundred feet upstream this unit consists of only the pyritic nodule layer, 3 inches thick.			
Logan Quarry coal			2½″ to 5″
Underclay			2′ 6″
Shale, drab, unevenly fracturing			5′ 6″
At about 1 foot above the base is a very black bed 3 inches thick.			
Holland Coal, dull			1′ 6″
Underclay			9′
Limestone			3′
Light tan, crinoidal, coarsely crystalline; brachiopods, cochliodont tooth; level of coal IIA?			
Dark gray fissile shale			3′ 6″
Two ½-inch carbonaceous bands at 2 inches and 6 inches below the top may represent Coal IIA.			
Drab unevenly fracturing clay-shale			15′
At the base, underclay with ferruginous concretions (position of Coal II?).			
Sandstone: massive; not conglomeratic at base			38′
Shale, brown			at least 3′ 6″

NEWPORT: Along the edge of the Wabash River flood plain south of Newport, several small steep tributary valleys incise the river bluff. Stratigraphic sections have been reported in several of these by Bradley, Ashley and others. We have examined the northernmost of these valleys, about a mile southeast of Newport, at the southern edge of the Newport quadrangle (see map, fig. 1). Other localities along the Wabash reported in this paper are Arketex (p. 63) and West Montezuma (p. 58). In the upper part of the section south of Newport, we incorporate Bradley's observation (1870, pp. 147–148); the detailed measurement of the Logan Quarry shale sequence is our own. It outcrops (1960) in a clean vertical exposure at an elevation of about 505 feet, on the right bank of the unnamed creek.

LINTON FORMATION			
Velpen limestone member			
Black calcareous ironstone	2″ to 2′		
Mecca Quarry shale member		3′	
Black shale, alternating soft gray and hard black.			
Coal IIIA			8″
Underclay, white		2′	
Sandstone, argillaceous		55′	
Possibly a basal member of the Linton formation. Bradley's reported 70 to 80 feet must be reduced to fit this section into the available topographic relief.			
STAUNTON FORMATION			
Shale, light drab		10′	
Black shale, mostly slaty		2′	
Lower Lodi coal		1′	8″
Underclay		10′	
With a persistent thin bed of hard sandstone containing *Stigmaria.*			
Logan Quarry limestone member		1′	
Fossiliferous calcareous ironstone.			
Logan Quarry shale member		2′	9½″
Soft black sheety shale (levels F and E?)	8½″		
With a major bedding plane 4 inches from the top.			
Black sheety shale; bottom half hard and massive. Acanthodian, sharks, *Pseudorthoceras* (level G)	3¼″		
Soft gray sheety shale (level H)	4″		
Black hard sheety shale (level J)	2¼″		
Soft gray sheety shale (level K)	5½″		
Black hard sheety shale (level Kb)	1¾″		
Soft black sheety shale	6½″		
Dunbarella, Pteria, Pseudorthoceras, orbiculoids, *Myalina,* driftwood.			
Finely bedded pyritic humulite	1″		
Poorly bedded slaty black humulite	¾″		
Logan Quarry coal: dull coal			¾″
"Underclay"		2′	11″
Gray soft shale, unevenly bedded, grading upward to underclay in the top 5 inches.			
Black shale, silty; thinly but unevenly bedded			6½″
Top ¾ inch clayey, unevenly fracturing; in the middle, it is a dark-gray shale, containing a dense aggregation of ostracode valves (coquinite). Contains orbiculoid, other phosphatic shells, fish scales.			
Underclay: dark gray, silty.			
Sandstone			

South Trumpet Valley: This valley joins Trumpet Valley at the base of the steep slope of the Wabash River Valley bluff (see map, fig. 19). Our section does not include measurement of the Logan Quarry shale sequence, for the exposure has weathered and the thickness of the beds is accordingly suspect. The thicknesses given will serve to illustrate the position of the Logan Quarry beds with respect to the key horizons above and below.

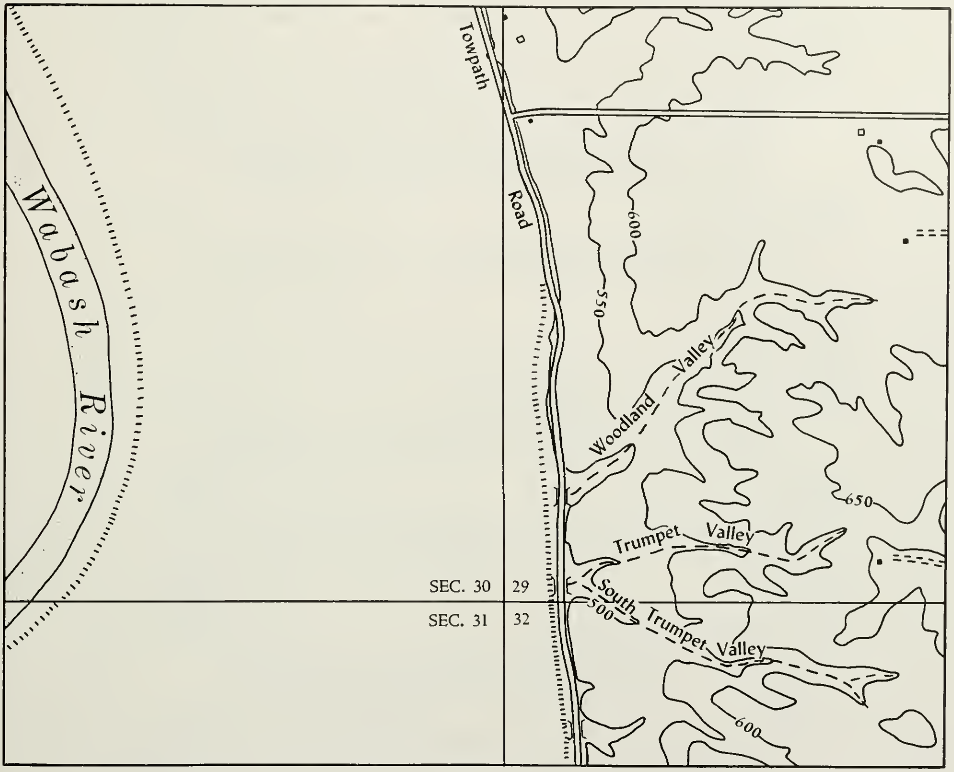


Fig. 19. Map of Trumpet Valley area, north of Sugar Creek. Scale: 4½ inches=1 mile.

On the edge of Towpath Road, about seven feet below the bottom of this section, two thin beds of coal were briefly visible following a regrading of the road in June, 1961. They are probably too close together to represent Coals IIA and II, and may together represent Coal IIA; they are recorded at the end of the following section. Somewhere not far beneath them there was formerly an exposure of Coal II, the Minshall limestone, and Minshall coal, if we have correctly understood the following reference by Hobbs (1872, p. 370): "A two-feet seam [of coal] and a less one are found outcropping in various places along the canal from Sugar Creek to Howard, covered by encrinite limestone."

The old canal, already in disuse at the time Hobbs wrote, may still be seen at the edge of the Wabash River flood plain, the former towpath now a minor automobile road still referred to locally as "the Towpath," but the banks of the canal are heavily overgrown and covered with soil and with debris deposited at high water by the river.

STAUNTON FORMATION

Shale, soft, carbonaceous, sheety, medium-gray	at least	1′	6″
Lower Lodi coal		1′	8″
Underclay		2′	9″
With a lens of sandstone, 0–2 feet thick at the base.			
Shale, blue-gray, unevenly bedded, unctuous		5′	
Logan Quarry limestone member (not measured)			
Logan Quarry shale and coal members (not measured)			
The thickness and succession are apparently almost exactly as at Trumpet Valley. Large concretions in level H are spaced as at Logan Quarry. In the green pyritic humulite and the black bed beneath it, all the *Myalina* are small. The typical thick dark brown coprolites usually found in this facies are present.			
Shale, sheety, gray, calcareous			5″
Shale, white sandy		3′	1″
With carbonaceous streaks, the white sandy shale grading upward to darker shale and gray calcareous poorly bedded silty shale.			
Sandstone		2′	
Shale, gray plastic			4″
Shale, gray friable		4′	
Holland limestone member, gray, dense	5½″ to		8″
Shale, black, carbonaceous, unevenly bedded		2′	8″
As in the clay pit below Garrard Quarry (see p. 73); this includes thin black harder layers with vertical fracture resembling coal.			
Shale, gray (underclay?)	at least		6″
Interval	about	7′	
The following units were seen on the edge of "the Towpath."			
Shale, gray	at least		1″
Coal IIA(?)			8″
Underclay	about	1′	
Sandstone, with plant fragments		1′	6″
Coal IIA(?)			6″
Shaly coal or coaly shale with root casts filled with sandstone.			
Underclay	at least		6″
Beneath this, it can have been no more than 15 feet down to the coals and limestone reported in the canal by Hobbs.			

TRUMPET VALLEY: Near the south edge of section 29 (T. 17 N., R. 8 W.) is Trumpet Valley, another of the formerly anonymous minor tributary gullies incised into the wall of the Wabash River Valley. At an elevation of about 540 feet, there were formerly two sylvan waterfalls where the stream tumbled over the hard black Logan Quarry shales just above a fork in the tributary. In the fall of 1960, these waterfall exposures were covered up by the spill from a small strip mine dug to the pyritic Lower Lodi coal about ten feet above the Logan Quarry section. Though the waterfall exposures have been destroyed, the stripping did expose some thirty feet of section in the headwall. In Trumpet Valley, as in Woodland and South Trumpet valleys, the green pyritic humulite with fossil vertebrates and invertebrates is exposed, though it is markedly thinner than at Garrard Quarry.

STAUNTON FORMATION

Sandstone, thin-bedded, soft, shaly	28′	
Shale, soft, gray, sheety, with plants	1′	
Lower Lodi coal	1′	1½″
Banded, with many thick beds of detrital fusain; very pyritic.		

Underclay		2′
Sandstone		5″
Shale, light gray, unevenly fracturing		8′
Logan Quarry limestone member		1′ 6″
Limestone, fossiliferous	4″	
Shale, blue, unevenly fracturing, unctuous (level E)	1′ 2″	
Logan Quarry shale member		3′ 4½″
Shale, soft, dark gray, well-bedded (level F)	3″	
Shale, hard, black, sheety (level G)	1½″	
Shale, soft, dark gray, sheety (level H)	8″	
Since this was measured on a vertical exposure, it is probable that hydration due to weathering has increased the thickness.		
Shale, hard black, massive to sheety (level J)	3½″	
Very similar to level G of the Logan Quarry type section. In two banks, tending to fracture across the bedding.		
Shale, soft, gray, well-bedded (level K)	6″	
As in level H this measurement may include expansion accompanying weathering.		
Shale, hard, black, sheety to massive (level Kb)	2½″	
Pseudorthoceras, orbiculoid; *Dunbarella* scarce in lower half, absent in upper half.		
Shale, soft, well-bedded, quite dark	2″	
Dunbarella abundant.		
Shale, harder than above, but fairly soft, very well-bedded; *Dunbarella* abundant	2″	
Shale, soft, dark gray, poorly bedded	4″	
Dunbarella abundant.		
Shale, hard, black	1″	
Dunbarella absent. At the top, 2 mm. of green pyritic humulite as known from Garrard Quarry. Contains *Myalina,* pleuracanthid shark teeth, thick dark brown coprolites.		
Shale, soft, dark gray, with no fossils	7″	
Logan Quarry coal member(?)		
Concretionary carbonaceous pyritic bed	4″ to 10″	
Underclay		2′ 7″
Very fine and plastic, laterally becoming sandy and containing odd-shaped concretions as much as 4 inches thick. Top inch dark and gritty.		
Sandstone, thin-bedded		1′ 10″
Shale, dark gray		6′ 4″
Covered interval		about 1′
Holland limestone member		8″
Impure gray argillaceous limestone locally with cone-in-cone structure	2″	
Impure dark gray very argillaceous limestone	6″	
Holland shale member, black, unevenly bedded, soft		at least 2′
Blackest at top, becoming dark gray beneath.		

WOODLAND VALLEY: Exposures in this valley and its tributaries (see map, fig. 19) constitute the most complete section we have seen in this part of Parke County. The Lower

Lodi and Holland coals have been removed by former small-scale mining, but without so disturbing the topography as to interfere with stratigraphic work. Woodland Valley is the most northerly of a series of steep incisions in the left wall of the Wabash Valley in which the Logan Quarry shales make prominent outcrops, forming waterfalls and steep-sided gorges.

LINTON FORMATION			
Underclay		1′	9″
Presumably beneath Coal IIIA, which, however, is not itself exposed.			
Sandstone			5½″
Light gray, fine-grained.			
STAUNTON FORMATION			
Shale, gray micaceous, with concretions		9′	9″
Sandstone, gray micaceous			4″
Shale, gray, with concretions		2′	8″
Sandstone			7″
Shale, gray		10′	11″
Shale, somewhat darker (medium-gray), grading downward to gray sandy micaceous shale		12′	
Sandstone			4″
Shale, medium-gray, grading downward to gray sandy micaceous shale		15′	2″
Lower Lodi coal			
The coal has been mined, leaving only a trace of bright coal.			
Underclay		1′	6″
Sandstone			2″
Shale, gray, grading downward to blue-gray irregularly fracturing clay shale with limy concretions (resembles level E of the Logan Quarry sequence)		7′	2″
Logan Quarry limestone member		2′	8½″
Limestone, varying in thickness from	8″ to 1′ 2″		
Middle is dense, gray, fossiliferous; top and bottom grade to dark gray argillaceous, very fossiliferous. Cone-in-cone structure developed very locally in dark argillaceous limy shale at base.			
Dark blue-gray irregularly bedded fossiliferous marine clay-shale (level E). In a branch valley this is 9 inches thick, with a 3 inch sandstone above it	1′ 6½″		
Logan Quarry shale member		3′	1¼″
Shale, dark gray, soft, well-bedded (level F)	6″		
Shale, hard, black, massive, in two benches (level G)	5″		
Shale, gray, soft, sheety (level H)	4½″		
Shale, hard, black, massive to sheety, in two benches (level J)	4¾″		
Shale, gray, soft, sheety (level K)	5″		
Shale, fairly hard, black, sheety (level Kb)	2″		
Dunbarella present in lower half, absent in upper half.			
Shale, gray, soft, somewhat silty, with *Dunbarella* abundant	8½″		
Thin-bedded evenly bedded pyritic humulite, green on bedding surfaces, with *Myalina* in upper half, numerous solid dark brown coprolites throughout; the stagnant-water facies of the Garrard Quarry section	1½″		
Shale		1′	2″
Black clay-shale; no fossils except for driftwood stems in the upper part and solid dark coprolites throughout; in the upper part, pyrite blobs and thin limy bands,			

with dense aggregations of ostracode valves (coquinite).		
Limestone (?fresh-water limestone)		1″
Shale	1′	9″
Gray irregularly bedded clay-shale containing an unconformity.		
Clay, light gray with limy concretions (?underclay)		2½″
Clay, light gray		11″
Clay, reworked		5″
Angular bodies of white clay, a few inches across, in a matrix of gray clay.		
Clay, gray		4½″
Shale, gray, sandy	1′	6″
Sandstone	1′	
Holland coal (mined out; indicated only by presence of underclay)		
Underclay		

MOREHEAD'S BANK: Bradley (1870, p. 147) reported an exposure of very fossiliferous black shale at "Morehead's Bank," one mile above Newport. Since he included conodonts, phyllocarids, and scales, teeth and spines of fish, we concluded that the Mecca fauna was present, the conodonts and phyllocarids, indeed, being especially typical of the Mecca Quarry shale member itself. Ashley (1899, p. 421) referred to an exposure of Coal VIA (IIIA), overlain by black sheety shale containing fish scales, on the "Morehouse" place, at the mouth of a ravine entering the Little Vermillion River from the south, but he also noted (op. cit., p. 414) that the portion of Bradley's section including the black shale was not to be seen on the south bank of the Little Vermillion. An old Vermillion County plat book giving the location of Morehead's land on that river also showed that the course of the river has changed since the middle of the nineteenth century, so that apparently the Morehead land would not now be on the river. Thus, the locality that we have found is not the old Morehead's Bank locality, but as it is certainly nearby and certainly exhibits black shales with the fauna reported by Bradley, we have retained the old name. The present exposure is in a recently dug coal-prospect trench in the left bank of the Little Vermillion River (SW ¼ SW ¼ SW ¼ Sec. 28, T. 17 N., R. 9 W.), about a mile and a half from the nearest part of Newport. In the spring of 1961 high water strewed sheets of black shale along the left bank of the river, and from them we recovered the following fauna, from the "A" and "B" levels:

Petrodus
Listracanthus
Edestus
Sharks, as articulated specimens, isolated cartilage scraps, gastric residues and teeth
Palaeoniscoids, as gastric residues and scattered bones and scales
Concavicaris
"Seaweeds"

LINTON FORMATION

Velpen limestone member			
A typical development of this member, very similar to its aspect in the headwalls of Mecca Quarry and the West Montezuma clay pit, with several thin concretionary limestone beds in the lower part of a succession of drab, unevenly bedded shales.			
Mecca Quarry shale member		1′	11½″
Black, fairly well-bedded, soft to hard shale (level A-plus)	6″		

Hard black and soft gray shale (levels A and B)	1′ ¾″	
Soft gray well-bedded shale (level C)	4¾″	
Coal IIIA		1′ 1″
With a ¾ inch parting 2½ inches from the bottom; a lens of sooty black material, 2 feet 6 inches wide and 2 inches thick within the upper bench.		
Underclay		5′ 6″
Sandstone		6″

STAUNTON FORMATION

Clay-shale, drab

Bradley quotes this unit as 30 to 50 feet thick, with at the bottom a series of ironstone bands and nodules that he correlates with a dark limestone at the mouth of the Little Vermillion River containing numerous tubicolous worms, probably equivalent to the Logan Quarry limestone.

Coal Creek Area: In the hope of finding more northerly exposures of the Logan Quarry shale, we examined several black shale outcrops on the lower course of Coal Creek in southern Fountain County. The sheety black shale exposed here overlies Coal IIA, in a much lower stratigraphic position. The entire aspect of the coal, the black shale above it, and the numerous limy layers above that, so much resembles that of the Mecca Quarry or Logan Quarry sequence that it should be recorded. This is all the more called-for because the black shale contains the Mecca fauna in its earliest appearance (so far as we now know) in this area.

Exposures of the IIA shale are to be seen in several places in section 36 (T. 18 N., R. 9 W.; see map, fig. 21), at elevations ranging from 517 to 535 feet. Some small abandoned strip mines at about 570 feet in the same vicinity probably exploited a higher coal. Black shale in the dumps of these mines, coupled with the elevation, suggests to us that the coal quarried was the Logan Quarry coal, and perhaps, if the mines were deep enough, also the Holland coal; both of these coals are exposed on Dotson's Branch (see p. 91), a half mile to the east and a little north.

Across Coal Creek, some 500 yards west of the exposures on the bank of the creek, is the abandoned shaft of the Silverwood Coal Company's Sturm Mine, of which Ashley gave the following section (1899, p. 292; we have added modern designations):

STAUNTON FORMATION

Shale, black, sheety	0′ to 6′
This shale is now exposed in the headwall of an abandoned strip mine on the left bank of Coal Creek, and in tributary gullies, but with a thickness of less than 2 feet.	
Coal IIA	1′ 6″
In the shaft, the elevation of the top of the coal was at 516 feet, assuming the elevation of the top of the shaft to have been 550 feet.	
Shale, light gray, argillaceous	8′ to 12′
Including, according to Ashley's revision (1909), Coal II a few feet above the Minshall limestone.	

BRAZIL FORMATION

Minshall limestone	4′
Elevation of the top of this limestone, probably 499 feet 6 inches.	
Minshall coal	4′
Shale, sandy	8′

According to Ashley (1899, p. 273: "This section I am not able to explain . . ."), the outcrops on Coal Creek were to be correlated with certain lower beds of the mine shaft exposure. However, we find that the correlation expressed above is reasonable. Similarly, this section may be correlated with several others in the vicinity, taken from the older literature (see map, fig. 20, and correlation chart, fig. 22). In none of these sections is Coal II reported; it may have been overlooked, or it may be developed only in local pockets. In most of the older sections, the Minshall limestone is thicker than we see it on Coal Creek; however, at that place it dies out entirely a few hundred yards from its thickest development. Likewise, in the unnamed tributary fed by Dotson's Branch just north of the creek-bank exposure, this limestone disappears locally by a lateral gradation to calcareous shale. This may be the reason for its absence in Cox's 1869 (1870, p. 119) section on the Lafayette Company's land (see fig. 22).

One of the cyclothems represented in this immediate area is the Silverwood, named by Alexander (1943, p. 143) ". . . because of the fine development of the marine member of the cyclothem around the town of Silverwood in southwestern Fountain County." We have not used this name because we were not confident of recognizing either the member or the locality from his description. However, it is probable that the lower part of the interval between Coals II and IIA is the marine member that he had in mind. The cyclothem was defined as including Indiana Coal II.

STAUNTON FORMATION

Sandstone with no basal conglomerate . . . . 3′ 7″

At the strip mine this is a marine sandstone in 2-inch beds containing *Antiquatonia*, *Composita* and an inflated pectinid; on the highway it is more heavily bedded, and also in a tributary just north of the highway where the lower surface is undulating, with a 4–5 foot wave-length, the crests of the waves aligned N–S; no marine fossils were seen at the latter localities. The thickness recorded is a minimum, measured at the strip mine (M, on the map, fig. 21).

Shale, drab, with limestone layers . . . . 5′ 5¾″

The thickness given is that at the strip mine; at the mine in the tributary north of the highway (TM on map) it is about 6 feet; in the highway cut (H) it is 10 feet 3 inches. The variation is probably due to an irregular bottom of the sandstone above. At the strip mine, the following section is exposed in the headwall:

Blue-gray shale	2′	6″
Limestone		2″
Blue shale	1′	7″
Limestone		2½″
Blue shale		5½″
Limestone		2″
Blue shale		1¼″
Limestone		2½″
Blue shale		1″

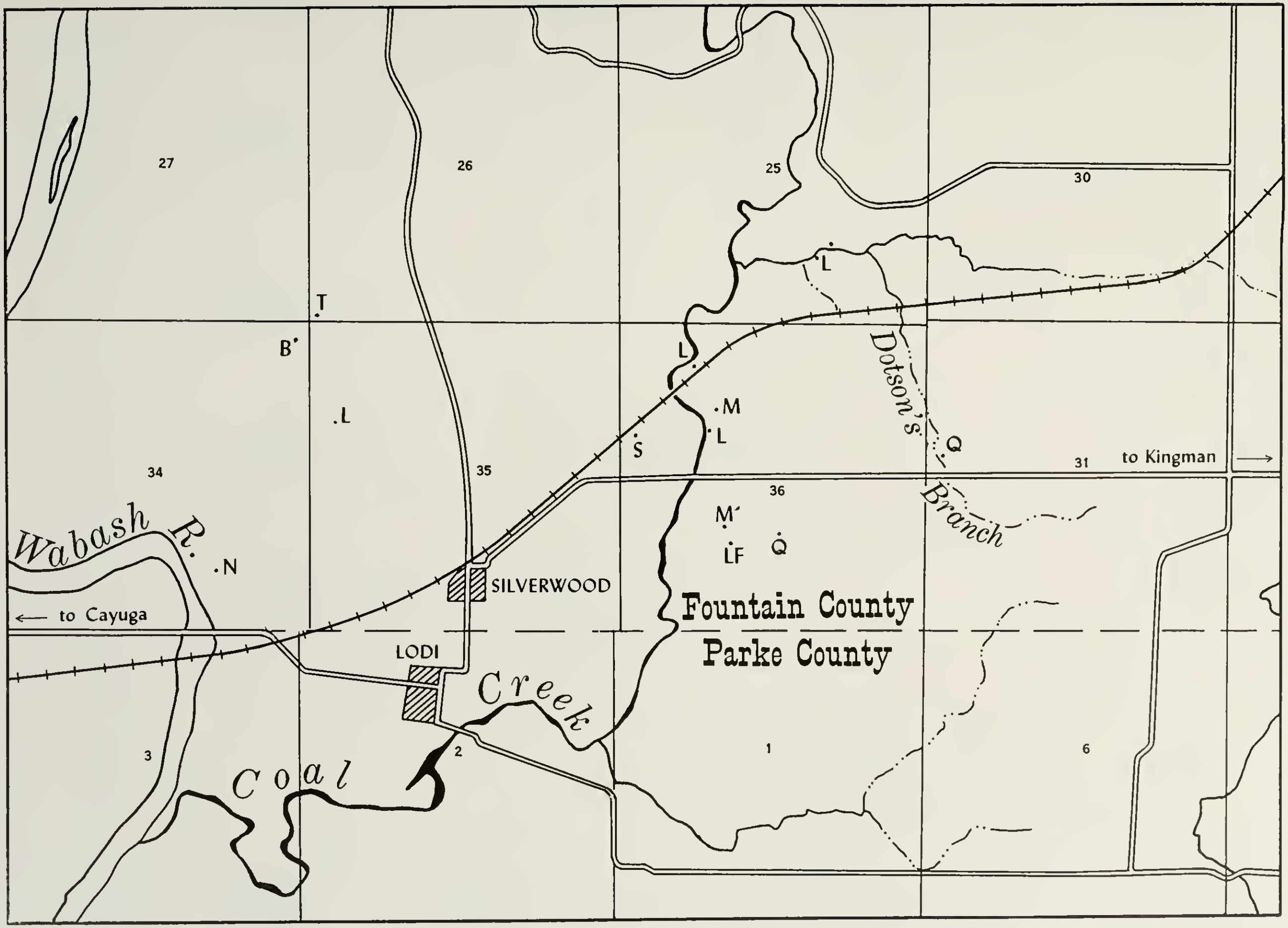
The last two units are replaced laterally by impure argillaceous limestone with *Desmoinesia*, corals, etc.

Black shale sequence . . . . 1′ 9⅞″

The thickness given is that at the strip mine; elsewhere nearby this unit varies from 1 foot 4 inches to 2 feet 4 inches. The sequence at the strip mine is as follows:

Shale, black, soft, sheety	2½″
Shale, black, hard, sheety	1⅛″

FIG. 20. Map showing lower course of Coal Creek in Fountain and Parke Counties. (B) Thomas shaft (Cox, 1870; later Indiana Bituminous Coal Company [see Ashley, 1899]). (L) Outcrops of Minshall limestone, 1961. (LF) Outcrop in left fork of tributary south of highway. (M) Abandoned strip mine on Coal Creek, in Coal IIA. (M′) Small mine tunnel in Coal IIA. (N) Section at Norbin Thomas' house, measured by D. D. Owen in 1838, by Leo Lesquereux in 1860 and by John Collett (*in* Cox, 1870), but now obscured by construction. (Q) Exposure of Logan Quarry shale in abandoned strip mine and on Dotson's Branch. (S) Sturm Mine of Silverwood Coal Company (operating in 1907, now abandoned). (T) Strip mine of Norbin Thomas (operating in 1869). Scale: $2\frac{3}{16}$ inches=1 mile.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Wabash R.
N
SILVERWOOD
to Cayuga
Fountain County
Parke County
LODI
Creek
Coal
3
2
1
6

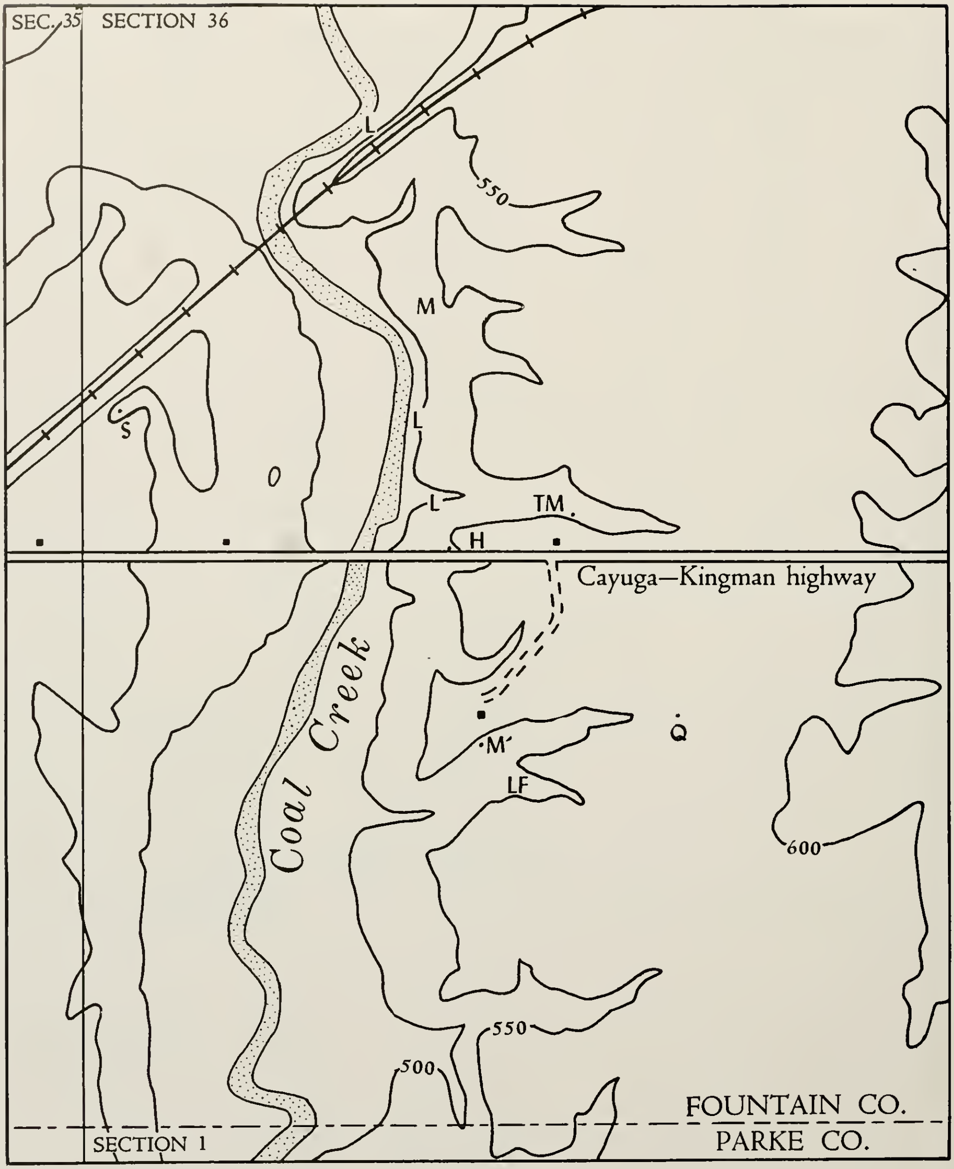
SEC. 35
SECTION 36
L
550
M
L
S
O
L
TM
H
Cayuga—Kingman highway
Coal Creek
M'
Q
LF
600
550
500
FOUNTAIN CO.
PARKE CO.
SECTION 1

FIG. 21. Detail map of Coal Creek area in southern Fountain County. (H) Exposure of Coal IIA on highway from Kingman to Cayuga. (L) Outcrops of Minshall limestone, 1961. (LF) Outcrop in left fork of tributary south of highway. (M) Abandoned strip mine on Coal Creek, in Coal IIA. (M′) Small mine tunnel in Coal IIA. (Q) Exposure of Logan Quarry shale in abandoned strip mine on upland. (S) Sturm Mine of Silverwood Coal Company (operating in 1907, now abandoned). In 1869 the land of the Lafayette Company lay somewhere in Section 1, T. 17 N., R. 9 W., probably a short distance south of the area covered in this map. Scale: 8 inches = 1 mile.

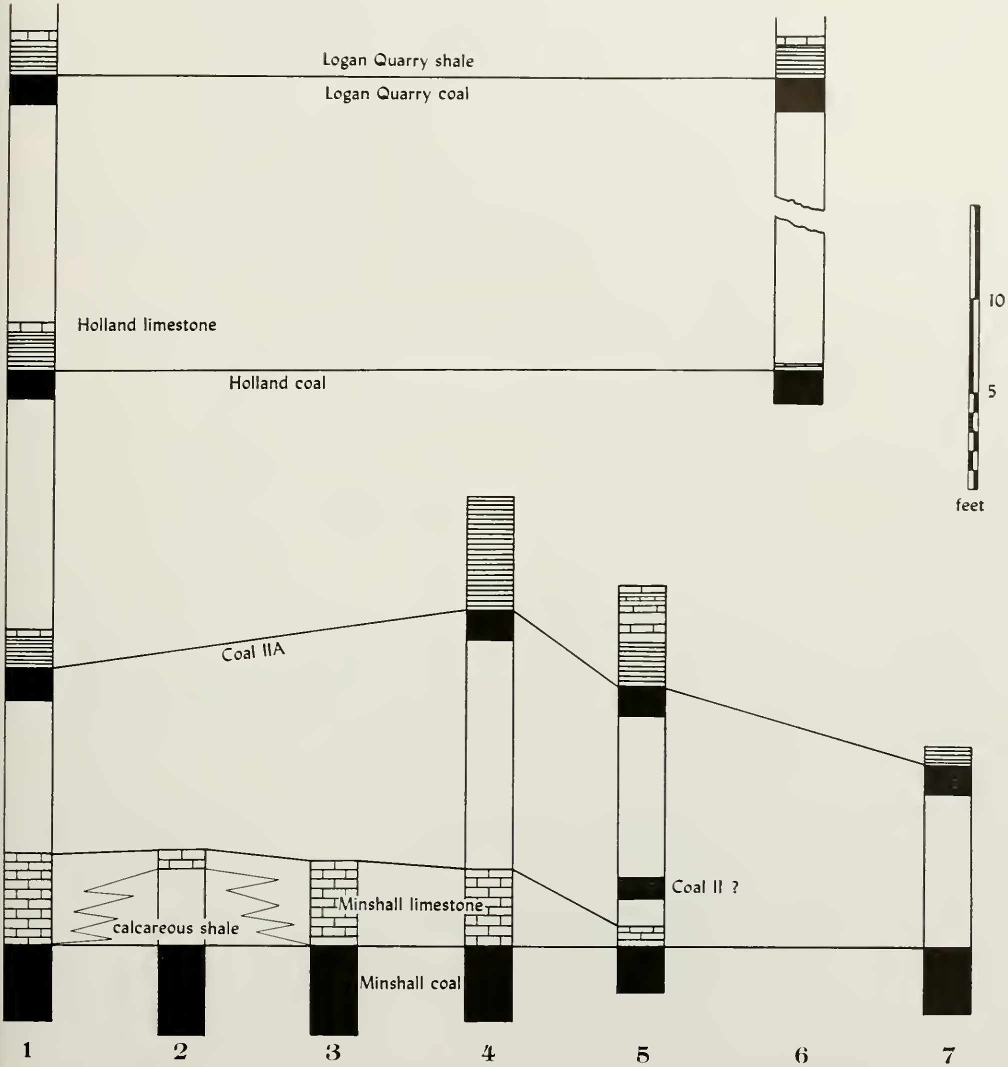
Logan Quarry shale
Logan Quarry coal
Holland limestone
Holland coal
Coal IIA
Coal II ?
calcareous shale
Minshall limestone
Minshall coal
10
5
feet
1
2
3
4
5
6
7

FIG. 22. Correlation of sections from Minshall coal to Logan Quarry limestone in Coal Creek area. (1) Bluff below Norbin Thomas' house, measured by John Collett (Cox, 1870, p. 120). (2) Thomas' shaft (Cox, 1870, p. 121). (3) Thomas' mine (Cox, 1870, p. 121). (4) Sturm Mine (Ashley, 1899, p. 272). (5) Bank of Coal Creek (our section, p. 91). (6) Dotson's Branch (our section, p. 91). (7) Lafayette Company, Parke County (Cox, 1870, p. 119).

Shale, gray, soft, sheety	2″
Shale, black, hard, sheety	1″
Shale, gray, soft, sheety	3¼″
Shale, black, hard, massive to sheety	1½″
Very similar to level J at Logan Quarry.	
Shale, black, fairly soft, sheety	1¼″
Shale, gray, soft, sheety	8⅝″
Shale, black, hard, massive to sheety	⅝″
Resembles level D at Mecca Quarry; contains orbiculoid brachiopods.	

At an outcrop in the left fork of a small tributary south of the highway (LF on map, fig. 21), the black shale sequence is 1 foot 4½ inches thick, with the following section:

Shale, black, hard, sheety	5½″
Contains cartilage and orodontid shark teeth, *Petrodus*, worm trails, *Pseudorthoceras*, driftwood.	
Shale, gray, soft, sheety	1½″
Shale, hard, black, massive to sheety	1¾″
Palaeoniscoid, driftwood.	
Shale, gray, soft, sheety	2¼″
—Plane of concretions.—	
Shale, black, hard, sheety	1¾″
Some seen in the float, probably from this level, had concretions in it.	
Shale, gray, soft, sheety	3½″
Shale, black, hard, massive to sheety	¼″
Dunbarella apparently not present.	
A thin film of shell breccia at the base is present at the mine (M′) in the right fork of this tributary.	

At an abandoned mine in the tributary north of the highway (TM), the black shale sequence is 2 feet 3¾ inches thick, divisible as follows:

Shale, black and dark gray, sheety	1′	4″
These beds resemble the succession of beds in levels A and B of Mecca Quarry. Fossils are relatively scarce, and include: *Petrodus* *Listracanthus* Palaeoniscoid scales Palaeoniscoid gastric residues Shark cartilage "Placoderm" fragments Acanthodian fragments *Pseudorthoceras* Coiled cephalopod Vertical worm tubes Driftwood		
Shale, gray, soft, sheety		11″
Shale, black, hard, massive to sheety		¾″
Dunbarella lacking; thin pyritic shell breccia at the base.		

Coal IIA	1′	6″

The thickness given was measured at the strip mine; at the other localities in the vicinity it varies from 1 foot 5½ inches (LF on map) to 2 feet (TM).

Interval . . . . 8′ 6″

This interval, including the Staunton-Brazil boundary, may be as much as 20 feet 6 inches if based on the topographic difference of elevation between the Minshall limestone and the coal exposed in the nearby strip mine. The value given here is computed with an allowance for dip from the elevations of the Minshall at the two more northerly points indicated by "L" on the map (fig. 21). The upper part of the interval consists of underclay; the lower part, as seen in the bank of Coal Creek near the strip mine, includes 4 feet or more of dark gray shale, unctuous, with sideritic concretionary beds, perhaps Alexander's Silverwood marine level.

The following units were measured on the bank of Coal Creek near the strip mine.

BRAZIL FORMATION

Coal II . . . . 1′ 2″

A dull coal, slabby, with fusain on the partings; soils the hands. This is the only place in the vicinity where we have seen this coal, which was probably deposited in local pockets.

Underclay, with sideritic concretions . . . . 1′ 5″

An inch or two at the bottom is an iron concentrate, weathering deeply to a soft red wad and perhaps representing a lateritic soil.

Minshall limestone member . . . . 8½″

Limestone, gray, fossiliferous.

Clod, black, with pyritic concretions . . . . 4″

Gradational to the coal beneath.

Minshall coal . . . . 2′ 5″

Two hundred feet upstream (north) from the creek-bank exposure where the members of the Brazil formation were measured, the Minshall limestone and Coal II have died out and the Minshall coal lies about three feet higher above the creek. Six hundred feet south of that same outcrop, the Minshall limestone is more than three feet thick; there it forms the roof of an abandoned mine tunnel in the first tributary valley north of the highway.

Dotson's Branch: On a brief reconnaissance visit, we found the following sequence on this small branch of a tributary of Coal Creek (see map, fig. 20). The name by which we know it is derived from that of the landowner through whose land we entered the upper reaches of the stream, where there is a good exposure of black shale. The section given is taken from both Dotson's Branch and a smaller branch that enters the major tributary about 400 yards to the west. Because of local dips that confuse the estimate of relative elevations, we have no value for the intervals between the key horizons.

STAUNTON FORMATION

Sandstone . . . . 5′

Shale, drab, with concretionary levels . . . . 5′

Logan Quarry limestone member . . . . 6″

Dark gray, bituminous, roughly bedded, with numerous crinoids and corals. Within a hundred yards this limestone disappears by facies change, becoming a calcareous shale almost indistinguishable from the shale above, but retaining the fauna of abundant crinoids and corals.

Logan Quarry shale member

Because of lack of a fresh exposure, we did not measure the thickness of this member. It consists of alternating hard black and soft

gray sheety shales, about a foot or somewhat more in thickness, containing the Mecca fauna, with fairly common *Dunbarella* in the lowest hard black bed and not above.	
Logan Quarry coal	1′ 8″ to 1′ 10″
A good solid coal that has been mined on a small scale for local consumption since at least the last part of the nineteenth century.	
Underclay	
Shale, sandy	
Interval	
Sandstone	6″ to 2′ 6″
Within the area of a small exposure in the creek bed, the sandstone shows this variation in thickness. Where it is the thinnest, it is underlain by the following succession of beds, some of which at least it replaces laterally.	
Ironstone concretions	0 to 3″
Shale, gray, with *Desmoinesia*	2″
The shells lie at all angles to the bedding.	
Shale, gray, very limy, with *Desmoinesia*	3″
In a stretch of about 4 feet of this bed, cone-in-cone structure is very well developed.	
Shale, gray, with brachiopods, corals and crinoids	5″
Holland limestone, gray, argillaceous	1″
Shale, gray	3″
Holland coal	1′ 9″
Underclay	
Interval, including sandstone, drab shale, Coal IIA with overlying black shale and underlying underclay, and concretionary sandy shale.	
Sandstone, with carbonized plant fragments	1′
Limestone	8″
Interval	
Underclay	

BRAZIL FORMATION

Shale, dark gray, fissile	at least 6′
Coal (II?)	2″
Underclay	4′
Interval	
Shale, blue-gray, fossiliferous, marine	8″
Minshall limestone	9″
With crinoids and *Taonurus.* Laterally, in about 50 yards, it thickens to 1 foot 3 inches; in about 100 yards farther upstream it grades laterally into gray highly fossiliferous limy shale.	
Shale, clayey, unevenly bedded	4′
Laterally, this becomes calcareous and concretionary.	
Shale, brown-drab, sandy	3′
Taonurus in the top 6 inches.	

HANGING ROCK: The name "Hanging Rock" occurs here and there in Indiana as a local appellation of a cliff, not necessarily overhanging. On the left bank of the Vermillion River (SE ¼ Sec. 20, T. 18 N., R. 10 W.), a massive sandstone forms such a cliff, with coals III and IIIA visible beneath it. While a reasonably fresh sample of coal may be secured, the shales above and below are deeply weathered and quite unsatisfactory for detailed stratigraphic description.

The section measured by E. M. Kindle in 1897 at Hanging Rock (Ashley, 1899, p. 404) is surprisingly similar to that measured by Neavel in 1960 (*infra*, p. 203). At the freshest part of the outcrop, we were able to measure a portion of the black shale sequence above Coal IIIA, which displayed the typical alternation of hard black and soft gray shale.

LINTON FORMATION		
Mecca Quarry shale member		
Hard? black shale	1″	
Soft gray sheety shale	3″	
Hard black sheety shale	1¾″	
Soft black sheety shale	2″	
Hard black sheety shale	2½″	
Fusain layer Bedded fusain in large fragments and detrital particles, with minor amounts of anthraxylon, in pure beds and as stringers in hard brown mudstone; pyritized and with blebs and stringers of chalcedony.	3″	
Coal IIIA		2′ ¼″
Coal	2¾″	
Parting	½″	
Coal	1′ 9″	
Underclay		3′

In the upper part of the underclay are hard light gray pyritic limestone concretions; locally, at the top, 1½ inches of black shale. At the bottom of the underclay, a soft black shale, well-bedded, with numerous fossils, lies on top of the upper bench of Coal III. This black shale contains:

Plant fragments (indeterminate fragments; fern pinnules)
Fusain
Coprolites
Conodonts (rare): *Hindeodella*
Ctenostome Bryozoa (rare)
Myalina
Dunbarella
Gastropods
Pseudorthoceras
Coiled nautiloid
Echinoid spines (*Echinocrinus?*)
Ostracodes (rare)

STAUNTON FORMATION

Measured at a short distance from Neavel's section

Coal III upper bench		2′ 6″
Clay parting		3′ 3″
Coal III lower bench	at least	1′ 7″

4. *Discussion of the Stratigraphic Evidence*

When the Minshall to Velpen interval is viewed on a regional scale and plotted in a series of profiles to show the depositional surfaces at different times (pl. 56) it seems clear that the overall down-warping of the edge of the Illinois Basin was not wholly uniform. Here and there local buckling produced topographic lows that were filled with much thicker sections of drab shales than at points nearby. In the entire area of observation there appears to be little evidence of regionally significant erosion. Two streams of sufficient competence to carry sand developed on the post-Holland surface; they remained as geographic entities throughout the time span covered in our study, shifting their position laterally to the north. The Coxville sandstone has been discussed by Friedman (1960). Details of the delta interrupting Coal III may be found in Neavel's discussion (p. 204 and fig. 46).

The Minshall to Velpen interval contains eight coals, each a member of an incompletely developed cyclothem (see Table 2). Transgressive sheety black shales overlie coals IIA, Holland, Logan, and IIIA; those over IIA, Logan and IIIA are similar in their detailed development, and so are the limestones above them.

Regressive, more or less sheety black shales are rare; the marine black shale lying upon Coal III at Hanging Rock is puzzling, inasmuch as Coal III is in general a regressive coal (Murray, 1958) and such a shale should lie beneath the coal.

While the Logan and Mecca Quarry shales are very similar as regards their microscopic structure and composition, their faunal contents, and the sharp alternation between black and gray levels, there are also significant differences. These pertain to the sediments on which the sheety shales have been laid down. In nearly all of the western outcrops of the Mecca Quarry shale, there are clod-filled channels containing productid brachiopods and corals, and the coal surface between the channels is covered with a shell breccia. In one locality, West Montezuma, there are productid banks that have certainly not been moved very far and that indicate proximity to fairly clear marine waters. This suggests that the Mecca Quarry shale along its present outcrop belt was deposited on the outer fringes of a coastal plain.

Productid-bearing clod-channels were never seen beneath the Logan Quarry shale. Instead, there is a variety of fresh-water deposits of deltaic character, including remarkable humulites that indicate stagnation in ponds and lakes (see below). The physiographic zone represented by the outcrop belt of the Logan Quarry shale is the flat, deltaic plain behind the fringe zone represented by the Mecca Quarry shale. It is very probable that the Logan Quarry Shale underground farther west would represent the fringe and should hence be expected to be virtually identical with the Mecca Quarry shale. Similarly, the deltaic hinterland facies probably existed in the Mecca Quarry shale east of its outcrop belt, where it is now eroded (fig. 51).

In figure 18 we offer a tentative correlation of the Logan Quarry shale and associated beds beneath, over an area of some twelve miles along the outcrop belt. Such uncertainties as exist are due mostly to the fact that exposures (except for Logan and Garrard Quarries) were weathered and hence did not permit a uniformly accurate determination of the rock character and fossil content.

In all profiles except Logan Quarry the transgressive sequence is preceded by fresh-water deposits, in contrast to the Mecca Quarry shale, where the transgressive beds invariably overlie the coal and the clod-filled channels. At Woodland Valley this fresh-water profile even includes a fresh-water limestone, as in the fully developed cyclothems of western Illinois (Weller, 1957). Here and at Newport virtually indistinguishable coquinites of dissociated ostracode valves (presumably also fresh-water) occur beneath the transgressive facies. At Woodland Valley the fresh-water limestone occurs above the underclay but below the coal-like humulite. At Newport the relation is the same, but the upper portion of the fresh-water sequence has become underclay beneath a thin coal.

The Logan Quarry coal, except at Collings Creek, seems to be an allochthonous deposit; in some places it is entirely absent and there is no evidence that the peat had been eroded.

At Dosdange Creek there is a fresh-water shale above the coal. Apparently it was a channel with very little current. The presence of pyrite concretions suggests near-stagnation. Lateral to this in corresponding position there are humulites containing *Myalina*. These are stagnant pond or lake deposits that all but lack clastic components (p. 113).

At some localities the humulite is overlain by fairly thick layers of dark gray to black often sheety shales, containing vast quantities of *Dunbarella* and other marine pelecypods. We draw the correlation line of the transgression at the base of the *Dunbarella*-bearing shales. It would appear that these ponds or lakes became saline following the stagnation phase. Evidently they were thickly covered with a *flotant*. The lack of marked alternation between gray and black zones in these levels may be due to forested higher ground nearby, which served to confine silt-laden streams to their proper channels. That such higher ground appears to have existed at Collings Creek is suggested by the relatively thick autochthonous coal and the very limited fresh-water humulite and *Dunbarella* section above. The physiographic picture suggested is that of a complex delta plain, some distance back of the delta margin (fig. 51).

By Kb time the topography appears to have been virtually leveled off, though thicker deposits of Kb at some places indicate that the delta surface was not a perfect plane. On this surface a sharply alternating sequence of high and low water sediments was deposited. The character of these sediments closely parallels that of the Mecca Quarry shale.

E. CHEMICAL, SPECTROGRAPHIC, AND MINERALOGICAL ANALYSES OF MECCA AND LOGAN QUARRY SHALES

1. Approximate Partial Chemical Analyses of Shale Samples

By

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Five samples were examined, two each from the Mecca and Logan Quarries and one from the Garrard Quarry.

Mecca and Logan Quarries: The Mecca samples are from levels B4 and C. The former is a black shale with partings parallel to the bedding. It is not readily cleavable and it fractures unevenly. There are numerous fragmentary organic remains and some vitrain-like lenses. The level C sample is gray, finely laminated fissile shale that weathers to a light gray. It contains sparse thin vitrain-like lenses.

The Logan Quarry samples are from levels G and K. The sample from level G is a black dense rock, and although it has a finely laminated appearance it breaks easily only infrequently along bedding planes and otherwise fractures conchoidally or irregularly. It has abundant fragmentary organic content and pyrite blebs. On weathering, a white or gray coating of sulfates is developed. The specimen from level K is a soft gray fissile shale which weathers to a lighter color.

These four samples were all subjected to the same procedures. Moisture was driven off by heating to 105°–110° C. and then the loss on ignition was determined by heating to 900° C. The proportion of the residues soluble in hydrochloric acid (1:1) was next found and then the loss in weight on treatment with hydrofluoric acid (plus a little sulfuric acid) was recorded as SiO_2. The residue was fused with potassium pyrosulfate, and total iron (as Fe_2O_3) was determined in this solution after adding the hydrochloric acid solution.

The following table gives the results of the analyses:

TABLE 4.—CHEMICAL ANALYSES OF BLACK SHALE SAMPLES

	Logan "K" %	Logan "G" %	Mecca "B4" %	Mecca "C" %
1. H_2O^-(105°–110° C.)	2.20	1.48	2.48	2.39
2. Loss on ignition (900° C.)	12.58	57.21	47.25	13.73
3. Soluble in HCl (after ignition)	2.29	5.15	4.32	5.18
4. Loss with HF (approx. SiO_2)	47.08	17.74	27.03	52.48
5. Residue after HF	35.84	18.42	18.92	26.12
6. Total Fe_2O_3 (in 3 and 5)	8.14	5.89	5.86	5.80

The loss on ignition represents, essentially, the loss of combined water and organic material, and oxidation of ferrous iron, particularly pyrite. Other reactions such as the calcination of any carbonate content may contribute a little. The portion soluble in hydrochloric acid includes iron oxide, particularly that after pyrite, and perhaps some alkalis and calcium and magnesium oxides. It is believed, however, to indicate approximately the pyrite content (as Fe_2O_3). The loss after treatment with hydrofluoric acid represents essentially the SiO_2 content. Total iron, as Fe_2O_3, includes that of the sulfides and of the ferro-magnesian minerals.

The large loss on ignition of the Logan sample from level G indicates a high organic content,[1] probably over 50 per cent; this is in agreement with the low silica and total iron content. Much of the latter is probably present as pyrite. The shale from level K, on the other hand, has a relatively low loss on ignition representing a content of less than 10 per cent of organics. This is concomitant with a high silica and therefore a high mineral content. Pyrite content is evidently much lower than in the level G sample.

The Mecca Quarry shale from level B has a high ignition loss and thus has a high organic content, probably over 40 per cent. Mineral content is accordingly relatively low and the pyrite content is relatively high. The sample from level C, however, has a much lower ignition loss, indicating an organic content of less than 10 per cent. Silica content and therefore mineral content is high and the pyrite content may also be relatively high, perhaps higher than in the B sample (although the relative high proportion soluble in hydrochloric acid may be due to other causes).

APPROXIMATE PARTIAL ANALYSIS OF HUMULITE SAMPLE FROM GARRARD QUARRY (from Zone 6): The sample from Zone 6 is very finely laminated (laminae from less than 1 mm. up to about 2 mm. in thickness) and is rich in very fine pyrite, which gives the rock a distinctly olive-green color. The laminae are layers of yellowish color, rich in pyrite, alternating with layers ranging in color from gray to black. There are rare streaks and lenses of calcite (<1 mm. thick), presumably representing shell material, and these are sometimes associated with pyrite. The portion of the sample analyzed had little or no calcite. Occasional lenses of brownish organic material also occur in the sample (coprolites).

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[1] After the manuscript of this paper had gone to the editor, we received a letter from Dr. Alfred M. Pommer, of the United States Geological Survey, reporting on the organic substances in a sample of the very black level G of the Logan Quarry shale at Logan Quarry. The pertinent portion of Dr. Pommer's letter is as follows:

> ". . . a portion of this specimen was extracted with chloroform and 1/1 alcohol-benzene, the acidic fraction of the extract separated from the non-acidic fraction, and the two fractions examined by infrared spectrophotometric techniques by Dr. Irving A. Breger, U. S. Geological Survey. . . . Dr. Breger reports that the organic extract contains a very complex mixture of acids and alcohols; the alcohols appear to be associated with aromatic structures. There are also additional unidentified components present. This extractable material does not appear to be of humic origin. The sample also contained a very large amount of insoluble organic material, which was not examined."

The treatment involved determination of the moisture content, loss on ignition, proportion of ignition residue soluble in hydrochloric acid (1:1), loss after evaporation with hydrofluoric acid (plus a little dilute sulfuric acid), and the total iron in the hydrochloric acid solution. The results are shown in percentages:

1. Moisture (H_2O^-)=0.92
2. Loss on ignition (900° C.)=49.01
3. Soluble in HCl=38.30
4. Loss after HF treatment=7.26
5. Residue after HF=4.51
6. Total iron in HCl solution (3) (as Fe_2O_3)=35.44

The total iron (in the HCl solution) was probably all, or nearly all, present in the sample as pyrite; on this assumption the pyrite content would be 53.23 per cent. The loss in weight on oxidation of this pyrite would be 17.79 per cent. The loss on ignition less the latter figure then becomes 31.22 per cent, which represents mainly the organic content and the combined water. The loss after HF treatment is the silica content, namely 7.26 per cent, while the residue (4.5 per cent) is complex but probably largely alumina and other oxides.

The sample is thus over half pyrite and nearly a third composed of organic material, and the residue (14.63 per cent) is mainly silicate but also includes the ash inherently present in the organic material. As the pyrite is syngenetic the rock represents a rather unusual sediment and the environment of deposition must have been markedly reducing and putrid.

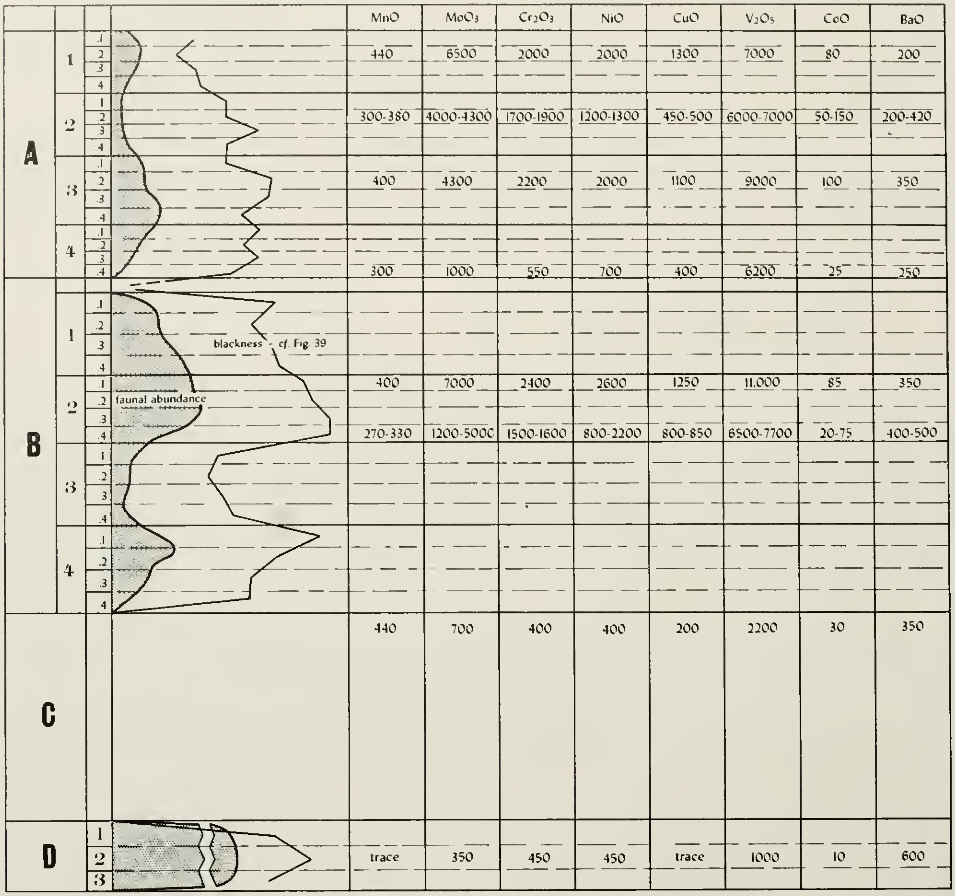
Microscopic examination of acid extracts indicates that plant degradation products are common (see also footnote, p. 96).

2. Spectrographic Analyses of the Mecca Quarry Shale

Spectrographic analyses of a number of shale samples from the Mecca Quarry were provided through the kindness of Dr. George W. DeVore, formerly of the Department of Geology, University of Chicago, to whom we wish to express our sincere thanks.

The results of these analyses are given in Table 5. The selection of the samples was not the most judicious possible, but it was made at a time when little more was known about the Mecca Quarry shale than the density of the fossil content. A number of elements in the samples from different levels differ strikingly in quantity. If the elements Mn, Mo, Cr, Ni, Cu, V, Co, and Ba are singled out, the suite of samples may be grouped into three categories, namely, the black level D, the light gray levels C and A4.4, and the remaining samples of black to dark gray levels.

The elemental concentrations are consistently high in the black and dark gray levels above level C, notably lower in the light gray levels C and A4.4. In the very black level D the concentrations are very low (except for Ba, which is higher than in the levels above D). The figures seem to indicate a rather striking difference between level D and the rest of the shale profile. Other evidence, however, is needed to explain the nature of this difference. Our interpretation of the origin and history of the Mecca Quarry shale is based on evidence entirely independent of its chemical composition.



			MnO	MoO₃	Cr₂O₃	NiO	CuO	V₂O₅	CoO	BaO
A	1	.2	440	6500	2000	2000	1300	7000	80	200
	2	.2	300-380	4000-4300	1700-1900	1200-1300	450-500	6000-7000	50-150	200-420
	3	.2	400	4300	2200	2000	1100	9000	100	350
	4	.4	300	1000	550	700	400	6200	25	250
B	1									
	2	.1	400	7000	2400	2600	1250	11.000	85	350
		.4	270-330	1200-5000	1500-1600	800-2200	800-850	6500-7700	20-75	400-500
	3									
	4									
C			440	700	400	400	200	2200	30	350
D		2	trace	350	450	450	trace	1000	10	600

FIG. 23. Diagram showing concentration of trace elements at selected levels of Mecca Quarry shale at Mecca Quarry, as related to fossil content and relative blackness of shale. Note relatively low concentrations in level D as compared to other very black levels farther up in the profile.

Level D contains a vast quantity of the marine pectinid *Dunbarella*. Its vertical distribution stops abruptly at the "D–C" boundary (see fig. 32). Level D lies immediately above the transgression shell breccia that covers the coal. Elsewhere in this study the alternation between gray and black levels was interpreted as the result of alternate high and low water periods, with the black levels representing times of residual ponding. The transgression shell breccia represents the initial flooding by marine waters from the adjacent epicontinental sea over the coal swamp, level D the first residual ponding period. Subsequently, however, the regime was primarily under the influence of incoming fresh water that produced the gray levels C, B3, and A4 to B1, that are rich in clastics (fig. 25). Levels B4, B2 and A3 are the corresponding low water periods. The transgression shell breccia and level D therefore differ strikingly from the rest of the levels by being primarily of marine origin, in contrast to the higher levels, which were deposited primarily in waters

TABLE 5.—CHEMICAL COMPOSITION OF SAMPLES OF MECCA QUARRY SHALE

Oiva Joensuu, *Analyst*

Level and analyst's laboratory number	5A1.2 (2143)	32A2.2 (2121)	33A2.2 (2142)	40A3.2 (2141)	41B2.1 (2140)	30B2.4 (2139)	41B2.4 (2138)	39A4.4 (2136)	Top of C (2137)	D (2135)
	%	%	%	%	%	%	%	%	%	%
SiO_2	59.0	60.0	60.0	65.0	60.0	62.0	65.0	70.0	70.0	72.0
TiO_2	0.85	0.95	0.90	0.90	1.10	0.90	0.90	0.95	0.95	1.05
Al_2O_3	20.0	20.0	22.0	20.0	18.5	22.0	21.0	21.0	21.0	20.0
Fe°	10.0	6.5	6.0	8.1	8.0	8.0	5.5	5.0	5.0	3.0
MgO	1.4	1.6	1.5	1.2	1.2	1.5	1.5	1.4	1.7	1.0
CaO	0.6	0.4	0.8	0.35	0.75	0.75	0.75	0.15	1.1	1.5
Na_2O	0.50	0.25	0.30	0.67	0.57	0.55	0.75	0.70	0.82	0.72
K_2O	4.35	5.50	5.20	4.30	4.55	4.70	4.70	5.00	4.60	4.20
	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
MnO	440	380	300	400	400	330	270	300	440	Tr.
MoO_3	6500	4000	4300	4300	7000	5000	1200	1000	700	350
Cr_2O_3	2000	1900	1700	2200	2400	1600	1500	550	400	450
NiO	2000	1300	1200	2000	2600	2200	800	700	400	450
CuO	1300	500	450	1100	1250	850	800	400	200	Tr.
V_2O_5	7000	7000	6000	9000	11,000	7700	6500	6200	2200	1000
CoO	80	150	50	100	85	75	20	25	20	10
ZrO_2	200	230	290	220	260	220	250	230	200	210
Y_2O_3	35	15	10	45	60	70	55	12	55	50
Yb_2O_3	13	6	7	10	12	12	8	7	5	5
Sc_2O_3	35	32	35	30	35	33	30	30	25	22
La_2O_3	50	70	70	80	120	120	80	70	80	77
BaO	200	420	200	350	350	500	400	250	350	600
SrO	180	180	300	200	200	230	180	150	220	200
SnO_2	20	100	8	3	20	100	15	25	25	10
PbO	450	150	200	250	140	100	90	100	80	50
Ti_2O	110	40	100	100	60	60	15	20	15	20
Sb_2O_3	220	150	100	150	150	200	X	X	X	X
CdO	+	X	X	+	+	+	+	X	+	X
Ag_2O	20	20	15	30	20	20	10	10	3	10
ZnO	500	180	100	>1000	>>1000	>1000	>1000	600	600	300
Ga_2O_3	30	25	25	30	35	30	30	35	35	30
I.L.	70.0	56.0	55.5	57.5	65.0	60.0	36.0	28.0	18.6	39.5

X = less than 100 ppm. but more than 50 ppm.

+ = about 100 ppm.

Quantities in the table are expressed as though the elements were present as oxides; Ag, Zn, Cd, Sb, Pb are probably present as sulfides.

Analyses are in terms of weight % of the ash.

I.L. = ignition loss in percent at 900° C. Fe° = weight % metallic iron; others are weight percent oxides.

derived from the hinterland. The concentrations of trace elements are very much lower in the black level D than in the higher black levels B2 and A3 and probably they reflect this difference.

The lower concentrations in the light gray levels C and A4.4 probably do not reflect lower mineral concentration in the water at the time of deposition but rather a much shorter time span involved in the deposition of gray shale, which contains large amounts of clastics, than of black shale, which contains but small amounts of clastics (fig. 25). The elemental concentration thus appears diluted in the light gray samples. This would not rule out the possibility that the high concentration of organic material in the black levels might have provided an environment more efficient for the fixation of the mineral content of the water, especially as regards elements such as vanadium, which are characteristically present as complexes with organic molecules in sapropelic sludges.

If our interpretations are correct, the elemental concentration values suggest that the waters of the epicontinental sea were relatively poor in mineral content while those from the land were notably rich. This, in turn, suggests the possibility of a significant disparity in the nutrient content of these two source areas.

It would seem that the unusually high burial density of vertebrates in the black levels above level D and the high elemental concentrations in these same levels are coincidental, in the sense that neither is responsible for the other. Both, however, are the result of the same cause, namely, the periodic lowering of the water level, which resulted, here and there, in residual ponding. On the other hand, if it be reasonable to presume that high elemental concentrations reflect rich nutrient environments, we may have a clue as to the reason why enormous numbers of fishes invaded the coastal lowlands during the periods of high water that followed level D time.

3. MINERALOGY AND PETROGRAPHIC CHARACTERISTICS OF SELECTED SAMPLES[1]

By

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During a visit I made to the laboratories of Chicago Natural History Museum, Zangerl and Richardson kindly showed me the wealth of unusual material on which their account of the geologic settings of the Logan, Mecca, and Garrard Quarries is based in large part. Some specimens were of interest to me because of their similarity to things found in the Pierre Shale of Late Cretaceous age in the western interior region, which is being investigated by the U. S. Geological Survey (Tourtelot, Schultz, and Gill, 1960; Tourtelot, 1962). Other specimens were of interest in themselves as results of various geochemical processes operating in sedimentary rocks. Subsequently, Zangerl and Richardson sent me a suite of specimens from which thin sections have been studied and X-ray analyses made. This note describes the mineralogy and petrographic characteristics of the individual specimens.

Specimens are referred to herein by numbers assigned to them by the laboratory of the U. S. Geological Survey, as shown in Table A. The numbers assigned by Chicago Natural History Museum are also shown in Table A; the provenience of the specimens and their relations to other kinds of data are to be found elsewhere in the report.

X-ray analyses were made according to a method developed by L. G. Schultz (1960). The results of the analyses are shown in Table A. The proportions of individual clay minerals in the total clay fraction could be determined only for sample CM-7. The mixture of kaolinite, illite, and mixed-layer montmorillonite-illite, and the absence of montmorillonite as a separate phase, are characteristic of many clayey rocks of Pennsylvanian age in the Midcontinent region (Grim, Bradley, and White, 1957, pp. 8–11; Schultz, 1958, p. 367).

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[1] Publication authorized by the Director, U. S. Geological Survey.

TABLE A.—MINERALOGICAL ANALYSIS BY X-RAY METHODS

(x: present but amount not determined)

USGS Sedimentary Petrology Lab. No.	Location and CNHM number	Material	Parts per ten of total clay					Percentage of whole rock							
			Montmorillonite	Mixed layer	Illite	Chlorite	Kaolinite	Total clay	Quartz	Plagioclase	Calcite	Gypsum	Pyrite	Apatite	Total
CM-1	Logan G; Li 4691	Black claystone	similar to CM-7					40	10	.	x[1]	.	25	.	75[2]
CM-2	Logan G; PF 2654	Oval coprolite; white lenses below coprolite	.	.	.	.	.	.	.	.	x	.	x	x	.
CM-3	Logan G; PF 2655	Round coprolite	.	.	.	.	.	.	.	.	.	.	x[3]	.	.
CM-4	Logan J; PF 2212	Shark fin	.	.	.	.	.	.	.	.	x	.	x	x	
CM-5	Mecca A 2.2; Li 4692	Lenticular concretion	.	.	.	.	.	.	.	.	90	.	.	.	90
CM-6	Mecca C; Li 4693	Doughnut concretion	.	.	.	.	.	.	5	.	90	.	5	.	100
CM-7	Mecca C; Li 4694	Laminated claystone and siltstone	0	5	3	x	2	60	20	2	.	.	15	.	97
CM-8	Montgomery Creek; Li 4695	Transgression shell breccia	similar to CM-7					25	4	.	35	.	30	.	94
CM-9	West Montezuma; Li 4696	Channel clod	similar to CM-7					35	7	1	7	5[4]	35	.	90

[1] Dolomite.

[2] Deficiency in total probably due to organic matter in sample.

[3] Sphalerite.

[4] Includes about 1 per cent jarosite.

The other samples contained too little clay or too much organic matter for results to be obtained within the limitations of sample and time available. X-ray traces obtained from some of the other samples, however, do not suggest any great difference in proportions of clay minerals from those in CM-7.

The petrographic characteristics of each specimen are described in the following paragraphs:

CM-1, Logan G, Li 4691, black claystone. The thin section is virtually opaque from organic matter and pyrite. Lenses of red-orange translucent organic matter 0.1 x 0.3 mm. are probably the anthraxylon of coal petrographers. Rhombs of dolomite about 60 microns in maximum dimension are scattered throughout the rock.

CM-2, Logan G, PF 2654, oval coprolite; and CM-3, Logan G, PF 2655, round coprolite. Both coprolites are made up of generally ovoid pellets of amorphous apatite (collophane) as much as 2 mm. in maximum dimension which Zangerl and Richardson tell me are fecal boli. Some pellets seem to be made up of smaller pellets about 0.25 mm. in diameter. Some of the larger pellets were soft at one time, however, because they have been partly deformed by surrounding pellets (see discussion of coprolite structure, p. 141). No bone structure can be seen in thin section and the pellets may contain considerable organic matter. The apatite is either a replacement of original organic matter or is a residue of phosphatic material in which structure was destroyed by the digestive processes of the fish or by diagenetic processes after the coprolite was deposited in the clay. The spaces between the pellets are largely filled with clear calcite that partly replaces the borders of some pellets and penetrates into cracks in other pellets. The calcite is confined to the interior of the coprolites and seems to have been prevented from extending beyond the coprolite by the layer of red-brown organic matter that surrounds each coprolite. The organic matter may be a remnant of an original mucous coating on the coprolite, or it may represent a concentration of organic matter that migrated out from the coprolite. Pyrite is not present in these coprolites. CM-2 contains several round masses of finely crystalline sphalerite about 0.2 mm. in diameter but none were seen in the thin section of CM-3.

Figure 36, *c, d,* shows the location and appearance of lenses of sphalerite in the compaction arcs below and to the side of each coprolite. Zangerl and Richardson tell me this is a consistent pattern of occurrence of sphalerite (see p. 165), and I believe the relation between the sphalerite and coprolite is a genetic one, as discussed below (p. 104). Sphalerite is an unusual mineral in this context and it was identified by an X-ray diffractometer trace of material picked from one of the lenses, and by a microchemical test for zinc made through the kindness of John W. Adams of the Geological Survey.

CM-4, Logan J, PF 2212, shark fin (fig. 40 and pl. 51, B–D). The prisms of amorphous apatite forming the exterior of the fin represent original calcified cartilage that must have consisted primarily of phosphate salts in life. Most of the original uncalcified cartilage that occupied the central part of the fin rays has been replaced with calcite in which there are a few patches of sphalerite. The calcite does not extend beyond the fin but there is little sign of a seal of organic matter such as was suggested for the coprolites. The calcite was deposited after the minor distortion of the fin, either by decay or compression (p. 179), had taken place. Sphalerite also occurs in lenses in the clay that filled the irregular depressions on the top of the fin.

CM-5, Mecca A2.2, Li 4692, lenticular concretion; and CM-6, Mecca C, Li 4693, doughnut concretion (see pl. 2, A). Both of these consist primarily of calcite, but CM-6 contains a little quartz and pyrite. The calcite varies considerably in crystal size, ranging from microcrystalline material with a clotted appearance to clumps as much as 0.05 mm. in diameter, the clumps being outlined with cubes of pyrite. The various crystal sizes reveal lenses and other irregularly shaped bodies that look like sedimentational units but seemingly are not. Lenses of black organic matter are fairly abundant.

The boundary between the enclosing shale and the concretion is preserved in CM-5. Apparently the calcite lenses partly replace and partly distend the clay and organic matter laminae. The boundary zone is very sharp for this sort of thing. Both concretions seem to be post-depositional cementations of partly consolidated shale. The abundance and continuity of the laminae within the concretion, as well as their lack of distortion, are perhaps the most significant criteria for this interpretation. Some compaction took place afterwards, of course.

A pair of *en échelon* gash veins crosses the slide. These are fractures filled with calcite and the sides of the fracture match each other. The calcite does not show characteristics of having grown in open space. The material along the fractures has been recrystallized locally.

CM-7, Mecca C, Li 4694, laminated claystone and siltstone. The rock is minutely laminated on a sub-millimeter scale, the laminations resulting from alternations in relative abundance of fragments of organic matter and lenses of clay. Quartz is within the clay lenses but is concentrated in a light-colored bed. Some of the clay lenses have layers at top and bottom that are more highly oriented parallel to the bedding than the material in the center of the lens. It is possible that many of the lenses are compacted pellets of biologic origin.

CM-8, Montgomery Creek, Li 4695, transgression shell breccia. The rock is a mass of shell fragments and other calcitic organic debris in a matrix of clay and red-brown organic matter. The calcite of the shell fragments is completely recrystallized, so that very little original shell structure can be seen. Calcite seems to have replaced clay along the margins of some shell fragments. Calcite also appears to have been deposited in soft masses that later were considerably deformed, or else the calcite replaces material that was deformed in the general mashing around to which the bed seems to have been subjected.

The most conspicuous feature of the rock is the extensive growth of pyrite in both shell fragments and matrix, especially in the red-brown organic matter. The pyrite is in cubes about 0.005 to 0.01 mm. in dimension, even where the pyrite forms a solid mass. The pyrite is not in the large crystals that I have come to think of as indicating replacement. The pyrite is later than the deformation of the red-brown organic matter. I cannot find any petrographic evidence that would place the deposition of the pyrite in time in relation to the recrystallization of the calcite.

CM-9, West Montezuma, Li 4696, channel clod. This rock is similar in type to CM-8, the transgression shell breccia, being made up of clay, calcite, and abundant pyrite. The clay is very opaque from organic matter, and considerable red-brown organic material is present. This is the only slide in which I found what appear to be plant megaspores. The calcite occurs as recrystallized shell fragments, although the fragments are very small. Calcite was deposited in the poorly preserved cells of a piece of coalified wood. Pyrite occurs in the calcite (as in CM-8) and in the matrix. The small amounts of gypsum and jarosite reported in the X-ray analysis resulted from the oxidation of pyrite, either on the outcrop or after the sample was collected, and neither gypsum nor jarosite was recognized definitely in the thin section.

Discussion of sphalerite: Sphalerite and other sulfides are not uncommon minerals in fish-black-shale associations, such as the Kupferschiefer, but I can find no description of an occurrence such as this one. Probably such occurrences exist, however, because Thomas and MacAlister (1909, p. 328) state that ". . . where these two sulfides [zincblende and galena] are met with in England, they always occur surrounding or replacing the soft parts of some organism." Westoll (1943) recalls occurrences of sphalerite, galena, and chalcopyrite associated with fish remains in the Marl Slate in England. He says, "So far as my recollection goes these minerals never replace bone but occur . . . between the dermal bones of the skull, etc." Ver Steeg (1940) reports sphalerite as fillings or replacements of crinoid stems and brachiopods in Ohio. Richardson (1956, p. 8) reports sphalerite on impressions of plant fossils and more rarely animal fossils in the Middle Pennsylvanian nodules at Mazon Creek in Illinois.

The zinc content of some modern fishes is as much as 5 to 10 times their iron content according to the data compiled by Vinogradov (1953, pp. 521–523, 525–526) and can amount to more than 100 ppm. in the living matter. Zinc thus is concentrated in some fish by several orders of magnitude above its content of 0.005 to 0.021 ppm. in sea water (Krauskopf, 1956, p. 3).

The hypothesis that appeals to me is that zinc released by decay of material in the coprolite migrates outward and is precipitated by hydrogen sulfide. Considering the rate of sedimentation that Zangerl and Richardson deduce (see p. 176), this migration would have taken place early but at a time when a few millimeters of sediment had accumulated over the coprolite. The solubilities of the sulfides of zinc and iron are sufficiently different to allow zinc to be precipitated and iron to move on. The zinc sulfide is concentrated in lenses slightly to the side of the coprolite because of the difference in porosity and permeability already effected by the minor compaction directly under the relatively hard body of the coprolite.

The relative masses of the coprolites and the associated sphalerite require, under this hypothesis, that the coprolites have had a very high zinc content at the time they were deposited on the bottom sediments. It seems at least possible that they had such a zinc content. The carnivorous fish that produced the coprolites had been feeding heavily on the abundant smaller fish in the locale of the present Logan Quarry (p. 140). The zinc content of the coprolites obviously depended on the zinc content of the food fish and on the metabolism of the carnivorous fish with respect to zinc, items on which no data can be obtained directly.[1]

The consistent association of sphalerite with coprolites and some fish remains in the Chicago Natural History Museum collections and the surprising zinc content of modern fishes suggest that coprolites consisting of fish remains are plausible sources for the zinc, although more data clearly are needed. Other sources for the zinc, such as the water in which the sediments accumulated, or the plant matter and other kinds of organic material in the rock, are possible, of course, and should receive consideration in any further investigation.

Calcium carbonate was precipitated within the coprolite at a later time after the coprolite had become a closed system in itself, either by compaction processes sealing it off or by alteration of the organic coating around the coprolite. (See discussion, p. 166.)

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[1] "What song the sirens sang and what name Achilles assumed when he hid himself among women, though puzzling questions are not beyond all conjecture."(Browne, 1658.)

F. THE MICROSCOPIC STRUCTURE OF THE MECCA AND LOGAN QUARRY SHALES

The microscopic structure of these shales is by no means uniform throughout the profiles: there are striking qualitative and quantitative differences between the recognized shale levels. The most conspicuous elements among the microscopic components are the plant decomposition products, which show notable similarities to certain elements in bituminous coals. We have searched in vain, however, for a comparative petrographic study of shales of this type and coal. An analysis of this sort is beyond our competency and should be done by a coal petrologist. This applies particularly to the translucent colored particles; the opaque material, on the other hand, appears to be so notably similar to micrinite (as defined by Hacquebard, 1952) that the use of this term for most of the opaque material in the shale seems justified.

The study of the microscopic structure of the Mecca and Logan Quarry shales as set forth below provides a significant body of evidence independent of other lines of attack in the present study. It may be of interest to the coal petrologist because the structure of the shale is far less complicated than that of coal, and because the paleoecological interpretations are based on evidence not available to students interested in the origin of coal.

1. *MICROSCOPIC COMPONENTS*

The microscopic components of the Mecca and Logan Quarry shales may be divided into three categories of different origin: clay, decomposition products of plants, and remains of animals.

a. CLAY: Clay minerals appear in vertical thin sections either as minute granules, or, more often, as lenticular areas interbedded with the other shale components. Under low magnification (125X) these areas are transparent, either perfectly clear, or, more often, containing granular and/or fibrous inclusions of other shale components. In sections parallel to the bedding these lenses appear as irregular patches of various sizes (pl. 10, H, I). The sharp marginal boundaries that are visible on vertical sections are rarely visible in horizontal sections, apparently because the sections are thicker than the fringe areas of the lenses, which thus are hidden from view by other shale components. The vertical size of these clay areas ranges from a few microns to about 100, but the usual thickness of clay lenses in gray shale levels ranges from 10 to 50 microns, in black levels from 5 to 20. The horizontal diameter of clay lenses in gray levels is from 200 to 500 microns, in black levels from 50 to 200.

b. DECOMPOSITION PRODUCTS OF PLANTS: Decomposition products of plants make up a large portion of the microscopic content of the Mecca and Logan Quarry shales; in black levels the shale consists of little else (pl. 6) and should thus probably be classified as coal. These levels, however, conform to black shale in all other respects, such as excellent horizontal splittability, lack of vertical breakability (thus great horizontal flexibility), excellent properties for the preservation of vertebrate skeletons and debris, formational joint pattern (see fig. 3), mode of deposition, relative scarcity of spore content, small amounts of sulfides (which are very common in the coal underlying the shale), and the fact that there are all possible transitional stages between these black levels and the relatively gray ones.

We realize that the problem of classifying these black levels as shale or as coal is primarily a semantic one. It depends largely on the direction of approach; to the student of black shales they are shale that approaches the status of poor coals; to the coal petrologist they are coals that approach the characteristics of black shale. Clearly, these levels hold an intermediate position between shale and coal and as such they should command the interest of both sedimentologists and those working on the problems of coal origin.

Since the black levels are an integral part of the Mecca black shale sequence and since there is no reason to believe that their mode of deposition was basically different from that of adjacent, slightly grayer levels, they will be treated as shale in the following description.

Examination of the decomposition products of plants in microscopic sections under transmitted light reveals two clearly definable components: completely opaque material, and substances that appear light brown or reddish-brown. In addition, the shale contains branches and even larger portions of tree stems (see p. 122) that appear in sections as sharply defined, reddish-brown lenses, usually without any recognizable structure.

1. *Opaque material:* In all shale levels, opaque substances make up by far the greater portion of the decomposition products of plants; only in a few extremely thin bands within certain black levels do the brown substances predominate. Here and there the shale contains macroscopic pieces of fusain, but these are infrequently encountered and none have been observed in any of the microscopic sections.

The bulk of the opaque material has granular or fibrous character in vertical sections (pls. 6–10); in horizontal sections it appears as irregular flakes (pl. 10, H, I), either so crowded as to suggest solid masses or loose enough to show granular structure. These flakes are very thin, 5 microns or less, and tend to form thicker aggregates (pl. 7, H, I, F), as is seen in vertical sections of light gray levels. In the darker levels the flakes appear to be much thicker, up to even 100 microns, but very thin flakes are also present. In view of the situation in gray levels where the opaque flakes tend to be vertically separated by clay lenses, we believe that the thicker bands in black levels represent thick, compacted aggregations of primarily thin flakes that are due to lack of sufficient quantities of interbedded clay. In some levels (for example, level D, Mecca Quarry) there are few well-formed clay lenses and few clearly discernible opaque flakes. Both materials usually occur in the form of small granules or globules that are horizontally arranged parallel to the bedding plane; or, as in the bottom black band of level M, Logan Quarry, the arrangement may be somewhat irregular, which accounts for the poor horizontal splittability of this level (pl. 7, A). In the gray layer of level M, Logan Quarry, the opaque material occurs in thick, compact bands separated by thick clay lenses. In transmitted light the above-mentioned opaque substances appear to be all of one kind. In reflected light, however, there appear to be two types of material: one reflects the light to some extent; the other is dull black. Such reflectivity as may be observed appears to be due to the presence of large quantities of minute sulfide crystals, and these seem to occur only in part of the opaque material.

2. *Translucent decomposition products of plants:* Under transmitted light, translucent, variously colored plant decomposition products may be seen interbedded among the opaques and the clay. The color ranges from dirty gray-green to faint light-brown to intense light-brown to reddish-brown to orange to bright lemon-yellow. With the exception of the bright lemon-yellow particles, which are rare and present only in dark black shale levels, the color of the translucent particles corresponds with the relative blackness of the shale levels; light-brown, reddish-brown and orange substances are typical components of the very black levels and are absent in light-gray shale horizons, which contain dirty gray-green substances. Faint light-brown to light-brown components characterize medium-dark shale levels. Just as there are all possible intermediates between light-gray and deep black levels

in the profile of the Mecca Quarry shale (see p. 97) there is an unmistakable gradient in the distribution of these colored substances in the direction set forth above. Quantitatively, the reddish-brown and orange substances may notably exceed the opaques in the deepest black levels (pl. 6) where the composition approximates that of coal. In the light-gray and medium-gray levels translucent plant substances play a minor role.

The microscopic appearance of the dirty gray-green to faintly brown substances in vertical and horizontal sections can best be described as vague smudges or stains in or around clay lenses; there are no clearly defined boundaries to these smudges, which seem to fade away into unstained adjacent areas. The brown material, like the opaques, appears flaky in horizontal aspect, fibrous in vertical section. The bright-brown to orange-brown components (pl. 6) form horizontal bands (in vertical section) much as in coal.

3. Sticks and twigs: All shale levels contain pieces of driftwood (see pl. 20) ranging in size from several inches in width and two or more feet in length down to very small twigs. Very small pieces of stem are frequently encountered in thin sections of the black levels as orange bands with clearly defined outline. Microscopic structures within these twigs were not observed; the orange material has an amorphous or floccular appearance.

4. Spores: Spores are rare inclusions in the sheety black shale. In microscopic section they appear, much as in coal, as small bright-yellow lenticles. The scarcity of spores in these shales is rather unexpected, since they must have been present in vast numbers at the time of deposition. Some mechanism seems to have prevented spores (and insects, see p. 128) from reaching the burial environment soon after falling into the water. A *flotant* covering the Mecca and Logan environments would have had such an effect.

c. Decomposition Products of Animals: The Mecca Quarry shale contains in many localities (for example, at the sites of Mecca and Logan Quarries) vast quantities of skeletal remains of lower vertebrates and a lesser quantity of invertebrates. Isolated scales, teeth, bones and bits of cartilage are frequently seen in sections and their preservation is usually good. Coprolites, with or without skeletal remains embedded within the fecal mass, are likewise very numerous (see p. 141). In view of the fact that vast numbers of animals decomposed in these sites, we must assume that some of the decomposition products of their soft parts are present in the shale (see footnote, p. 96).

2. *VERTICAL DISTRIBUTION OF MICROSCOPIC COMPONENTS*

In the following discussion, the qualitative and quantitative distribution of the microscopic shale components other than animal remains will be described for the profiles at Mecca and Logan Quarries.

a. Logan Quarry: The profile at Logan Quarry consists of a sharply delimited alternating sequence of black and gray levels of fair thickness (see p. 67). By and large each of the levels is relatively uniform in color and character (except for levels G and J) and for this reason it was not considered necessary to prepare thin sections of the entire profile. The following set of thin sections is available:

Level	Slide No. (v=vertical; h=horizontal)
F	8v, 37v, ?7h
G	3v, 12v, 33v, 39v, 5v
H	1v, 26v, 19h, 21h, ?7h
J	4v, 6v, 11v, 25v, 9v, 13v, 17v, 22v, 23v, 24v, 14h, 15h, 16h, 18h, 20h, 2h

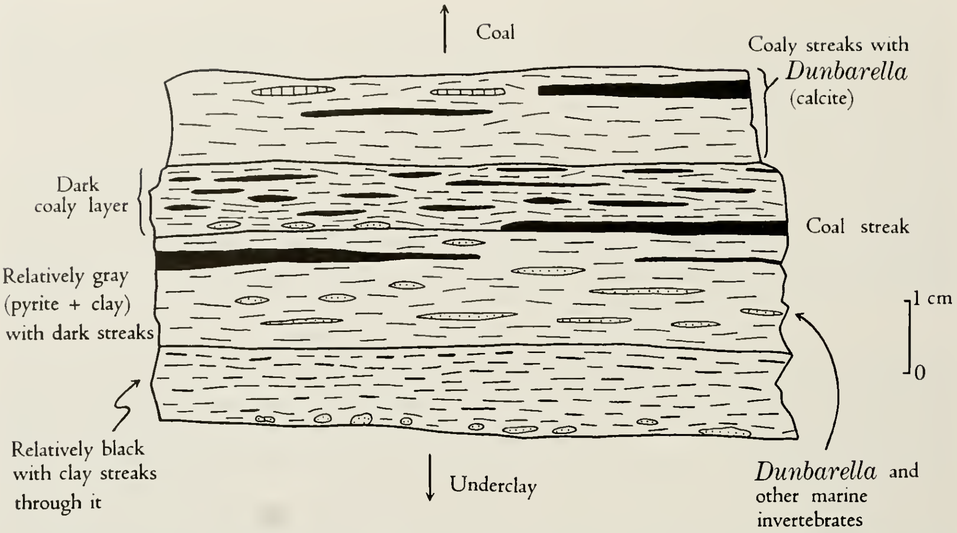
Coal
Coaly streaks with *Dunbarella* (calcite)
Dark coaly layer
Coal streak
Relatively gray (pyrite + clay) with dark streaks
1 cm
0
Relatively black with clay streaks through it
Underclay
Dunbarella and other marine invertebrates

FIG. 24. Detail of composition of level M at Logan Quarry, drawn from a block cut transverse to the bedding.

Level	Slide No. (v = vertical; h = horizontal)
K	46v, 40v, 55v
L	43v, 44v, 45v, 28h, 31h
coal	10v, 29v, 30, 36v, 38h, 124h
M	41v, 57v, 32h; 42v (M-underclay boundary)

1. *Qualitative description:* Level M (pl. 7, A) is about 55 mm. thick, dark gray, and poorly splittable; it contains large quantities of sticks and twigs interbedded with clay, opaques (including quantities of sulfides), and brown elements. The composition is not uniform. Macroscopically there are two bands of dark carbonaceous material and two bands, each about 10 mm. in thickness, which are slightly lighter gray (fig. 24) and contain poorly preserved *Dunbarella*. Microscopically, level M contains three readily distinguishable shale types that occur repeatedly in various sequence combinations. Two types are found in the blackish bands: in one type light-brown elements predominate and variously sized orange elements are very common; very few flaky opaques are present and the granular opaques are mostly sulfides; there is little clay and it does not occur in lenticular forms. The other type contains quantities of flaky opaques and sulfides, little brown and orange material and a modest amount of clay distributed between the opaques in a vaguely lenticular form. The grayish bands of level M consist of densely packed, replaced (calcite) shells of *Dunbarella* separated by layers of flaky opaque material and large amounts of sulfides. Brown elements are relatively scarce.

Coal: See discussion by Neavel (p. 198).

Level L (pl. 7, B) varies in thickness from about 10 mm. to (locally) over 50 mm. It is almost black in color with an olive green cast on vertical section. It is well bedded but not easily splittable horizontally. It consists primarily of well-bedded bright-brown, orange, and yellow material and large quantities of sulfides; there are no flaky opaques, but rodlike, completely opaque structures and fusain splinters can be seen in horizontal sections. The rodlike objects can be seen on the bedding planes under the binocular microscope and appear to be fibrous remnants of plants (leaf-ribs?). The brown and orange substances are either vaguely outlined flakes, or marginally well-defined structureless plant fragments. Clay appears to fill the small interstitial spaces between the components described, and somewhat larger amounts occur in some thin bands, where it is bedded with lesser amounts of opaques and browns. Locally, pyritized, well-preserved invertebrates, including a nautiloid cephalopod, were collected. The very top surface of level L contains large numbers of *Dunbarella*. The base is almost identical with the humulite of Zone 5 at Garrard Quarry.

Level K (pl. 7, C and D): From this level on to the top of F there is an even-bedded sequence of black and gray shales, starting with the black level Kb. Kb is not separated from the rest of level K by a sharp bedding plane and was thus quarried out with it as one level of about 165 mm. thickness. Kb grades upward almost imperceptibly into the much thicker gray portion of K. In vertical section, Kb (lacking about 25 mm. in the thin section) consists very largely of flaky opaques (with relatively minor amounts of sulfides), lenticular as well as finely distributed clay, and a great number of small, bright-orange to red twigs or even lesser plant remains, and occasionally a larger stem fragment. There are few brown elements. Toward the top of Kb the clay assumes more and more typically lenticular form and the lenses increase in number; the bright-red and orange plant debris fades to light brown and becomes less plentiful. The flaky opaques become better separated from each other by clay. Above Kb the browns are replaced by dirty gray-green smudges that give the clay the appearance of impurity (pl. 7, D). Near the top of Kb the clay lenticles are small, around 10 microns in thickness, and very numerous; toward the middle of K, where this level is grayest, their thickness is around 50 microns.

Level J (pl. 7, E, F, G, H) is a very well-defined, hard sheet of dark gray to black shale about 33 mm. in thickness. Six mm. below the top surface there is a deep black band, 4 mm. thick. This black band is of particular interest because it directly overlies the beautifully preserved large shark (skin with shagreen intact) (see pl. 24, B). About 10 mm. above the bottom surface of level J there is a well-developed bedding plane and the shale below it (Jb) is clearly transitional betweeen levels K and J. Two mm. from the bottom there is a black streak about 1 mm. thick.

In this transitional band (Jb) the clay lenses diminish in thickness to 10 microns for the most part; thicker lenses exist but are uncommon (pl. 7, E). Light-brown material increases toward the middle of level J. In the lower thin black streak there are abundant thin red and a lesser number of yellow elements embedded in what looks like a matrix of flaky and granular opaques (fusain debris?). Clay lenses are few and thin. From this point upward to the surface of Jb the shale differs from that below the lower black streak in that the clay lenses are generally thinner and the light-brown material increases in quantity.

Above the bedding plane separating Jb from J proper, there is a distinct change in the character of the shale components. Bright yellow and red elements are as conspicuous as the flaky opaques, which are sharply delimited, uneven in thickness, and very dense. Most of the thin clay lenses contain granular opaques, probably fusain splinters. The upper black band of level J is very dense (pl. 7, F, G); flaky opaques and brilliant red and orange constituents are tightly packed. Clay occurs in the form of exceedingly thin lenses full of granular opaques and a very few thicker (20μ) lenses that may or may not contain opaque debris. The rich red elements are very thin (2 to 10μ; pl. 7, G).

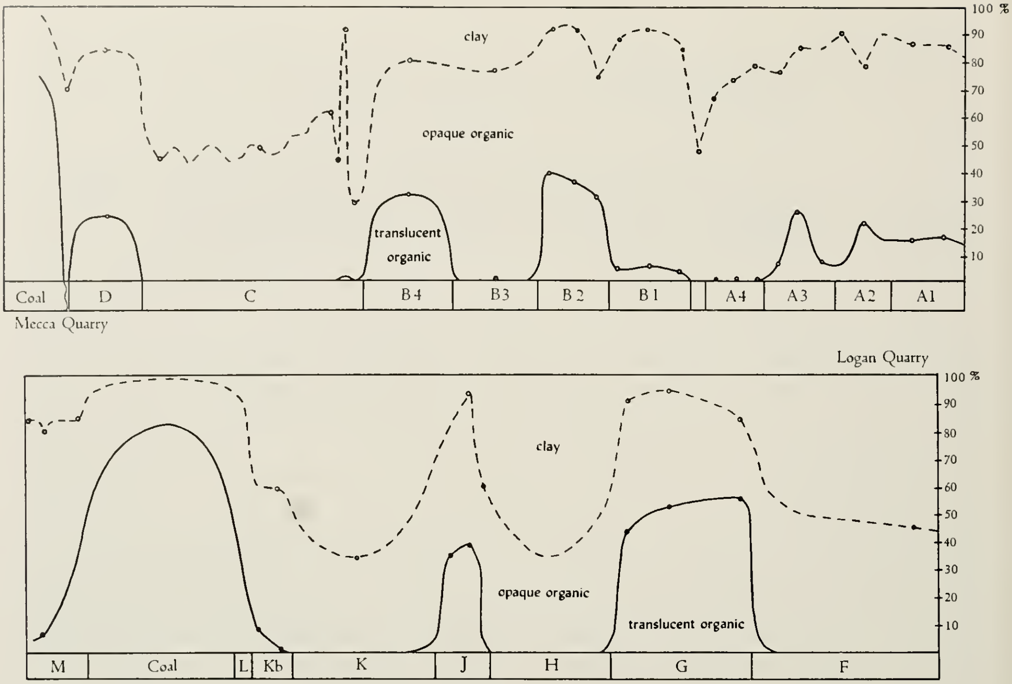

FIG. 25. Relative abundance of clay and translucent (colored) and opaque decomposition products of plants in microstratigraphic levels of Mecca Quarry shale at Mecca Quarry and Logan Quarry shale at Logan Quarry. Values expressed in percentage of total.

Above the black band the shale changes again in character. Flaky opaques of various thicknesses and clay lenses up to 50 microns thick and almost always full of opaque debris are the principal ingredients. There are very few red elements, and the browns are all but missing (pl. 7, H).

Level H (pl. 7, I) is a gray bed about 90 mm. thick. Although it may be virtually impossible to tell this level from other gray beds (such as K or F) by macroscopic inspection, it is clearly characterized by its microstructure. The clay lenses are often very thick, 100 microns or more, and they are full of angular opaque debris and gray-green smudges. There are no brown or orange elements. Occasionally a twig or stick has the usual red color. Dense flaky opaques separate the lenticular clay bodies.

Level G (pls. 6 and 8, A and B) is 90 mm. thick, black, and very dense. There are only two bedding planes along which level G will split regularly in unweathered condition. One lies 20 mm. above the bottom surface, the other about 60 mm. Small pieces of this level will, of course, split at many other points of the profile. The middle portion of level G resembles microscopically the upper black band of level J: there are large amounts of bright red and orange, but here in addition browns and flaky opaques make up the bulk of the material; there is very little clay. Toward the bottom of the level the opaques are somewhat more numerous; toward the top, where they are less abundant, there are rich browns and orange browns.

Level F (pl. 8, C), about 160 mm. thick, and dark gray, is the uppermost sheety shale at Logan Quarry. It consists of clay lenses of moderate thickness, rarely exceeding 30 microns, and much flaky and granular opaque material. Compared to levels K and H, this shale is less regularly bedded and the opaque material is more diffuse in its arrangement. There are no brown or orange elements; instead, as in the other gray levels, there are gray-green smudges and occasional faintly brownish structures as well as dull red sticks.

2. *Quantitative description:* The quantitative compilation of the microscopic components is based on averaged counts of 5 traverses at each selected point of the profile. Three categories of structures were counted: opaques, browns with reds, and clay. Faintly brownish elements and gray-green smudges were disregarded because they have no clear boundaries. The results are charted (fig. 25). On the whole the chart shows a good inverse relationship between brown-red elements and clay, except at the base of level M. The opaque elements, on the other hand, show little relationship to either of the other two curves. The noteworthy fact is that they constitute less than 30 per cent of the total at only one point (top of level G) and most counts show an opaque content between 40 and 60 per cent. Clearly, opaque material developed fairly constantly during the entire sequence of shale deposition and does not seem to have much to do with the particular circumstances that produced either black or gray levels.

b. Mecca Quarry: The profile at Mecca Quarry is somewhat more complicated than that at Logan Quarry (see stratigraphic section, p. 45). There is also an alternation of black and gray levels, but the contrasts are often, especially in the upper portion of the section, not as sharp as at Logan Quarry. Furthermore, the shale is not uniform in character even within thin levels in this upper part. Vertical sections of these levels show alternations of lighter and darker streaks so numerous that they cannot be described separately. An almost continuous set of vertical thin sections was prepared, as follows:

Level	Slide No. (v=vertical, h=horizontal)
A1	53v, 65v, 66v, 73v
A2	48v, 56v, 72v
A3	61v, 72v, 54h
A4	50v, 59v
B1	68v, 70v, 71v, 75v
B2	51v, 64v
B3	58v
B4	60v, 67v, 74v
C	62v, 69v, 52v, 47h, 49h
D	34v, 78v, 35h

1. *Qualitative description:* Level D (pl. 8, D, E) is about 25 mm. thick. It is a deep black layer which, in microscopic structure, resembles level L of Logan Quarry to some extent, although macroscopically the resemblance is minimal. Clay occurs either in thin lenses or in granular form. The opaques are commonly granular or angular (?fusain spicules) or, rarely, flaky. The colored elements are very thin flakes of pale orange and brown shades; bright colored components are all but absent.

Level C (pl. 8, F, G, H) is about 75 mm. thick, and is light gray, except for a darker band 6 mm. below the top surface. Below this dark band the shale contains rather large quantities of flaky opaques that tend to be packed into thick black streaks, sometimes more than 100 microns in thickness. The clay is lenticular and packed with angular opaque debris; gray-green to faintly brown smudges are seen all through the section. There are very few brown or even pale orange elements present, in contrast to what was seen in the gray levels at Logan Quarry.

The dark gray band near the top of level C consists primarily of flaky opaques, packed into many layers about 100 microns thick (pl. 8, G). Most of the clay lenses are very thin, 10 to, rarely, 30 microns thick, and they are less muddy in appearance than in the grayer shale. A relatively small quantity of very thin (5 to 10_μ) fragments of orange material is present but there are no bright brown elements.

Above the black band the shale is primarily composed of clay lenses that are only moderately muddy (pl. 8, H). The flaky opaques are, on the whole, less notably packed. Faint brown stains are present, along with an insignificant number of brownish flakes.

It may be noted that the grayest level at Mecca Quarry, level C, which looks macroscopically very much like levels K and H at Logan Quarry, does contain a certain, though negligible, amount of colored material.

Level B4 (pl. 8, I) is a black level, about 30 mm. thick. Opaque and colored materials are present in about equal quantities and there is a notable amount of clay which occurs in the form of lenses up to 30 microns thick or as minute granules. The clay may contain opaque debris, but often it is quite clear and it may even contain light-brown elements. The opaques are mostly flaky and thin and are interbedded with rich red, orange and a minor quantity of brown flakes.

Level B3 (pl. 9, A), a dark gray band about 30 mm. thick, contains a number of alternating darker and lighter streaks. In its microscopic composition it resembles other gray levels, but the content of flaky opaques is very high indeed, especially in the darker streaks, where the interspersed clay lenses are few and very small. In the lighter streaks the clay lenses, containing much opaque debris, may reach more than 50 microns in thickness. Save for faint smudges there are no colored elements.

Level B2 (pl. 9, B–D), 25 mm. thick, is the third black level from the base of the profile. It is similar to B4 in structure, but much of the opaque material is angular debris, and flaky opaques are present in smaller quantity. The clay, furthermore, tends to be granular rather than lenticular (although some clay lenses do occur) as in B4. The character of the colored components is much the same as in B4.

Level B1 (pl. 9, E, F) is about 28 mm. thick and very dark gray. It is very dense, consisting almost wholly of opaque material, mostly flaky in character. There is very little clay, and it is arranged mostly in very thin lenses rarely exceeding 20 microns in thickness. Much of it is granular. There are colored elements, but these are tiny pale orange flakes mostly less than 50 microns in diameter.

Above B1 there was a thin band of light gray shale which was so friable that it could not be preserved. No sections of this are available.

Level A4 (pl. 9, G–I) is 20 mm. thick, dark gray and finely banded. It contains more clay than B1. The clay occurs here in lenses up to 50 microns thick, though most of them are thinner. There are no colored elements to speak of, but faintly colored stains are common. Both flaky opaques and angular debris are present. In some of the darker horizontal bands of A4 the opaques are very dense, much as described under B3.

Level A3 (pl. 10, A–C), 25 mm. thick, again shows alternating bands of darker and lighter shale. Both the top and the bottom quarters of A3 contain very few colored elements, but notable quantities of rich orange elements are found throughout the middle half.

Near both top and bottom, clay occurs in lenticular form, usually no more than 20 microns in thickness, but one large lens reached nearly 150 microns. The opaques are mostly flaky, forming, particularly near the top, thick black bands. In the middle of the section both the opaques and the clay are more granular. Clay lenses are few in number and small in diameter (100μ or less).

Levels A2 and A1 (pl. 10, D–G), 20 and 25 mm. thick respectively, are similar in composition and microscopic appearance. Opaques are the predominant substances, occurring mostly in the form of small, usually fairly thick (50μ) flakes, or as dense, almost solidly black bands. The distribution of the clay is irregular and patchy. Clay is present in moderately thick lenses as well as in granules and in streaks of less than 10 microns. In both levels there are colored elements in the form of small orange-brown flakes.

2. Quantitative description: The quantitative compilation was done in the same manner as for the Logan Quarry profile (p. 111). The chart (fig. 25) shows the characteristic alternation between levels with colored materials and levels lacking them. To this extent, the situations at Mecca and Logan Quarries correspond well. In other respects, however, there are differences. The clay content does not (except in level C) increase where there are few or no colored substances, as is so clearly apparent in the Logan Quarry profile. Furthermore, at Mecca Quarry the opaque content is generally higher than it is at Logan Quarry. Because of the high opaque content in levels B4 to A1 there is no striking alternation between gray and black levels, and differences are more subtle.[1]

From A3 upward the alternation between levels with and levels without colored material ceases, even though there are quantitative differences in the occurrence of such substances.

c. Garrard Quarry, Fresh-Water Facies of Logan Quarry Shale (fig. 16): The microscopic structure of the fresh-water facies of the Logan Quarry shale at Garrard Quarry was studied only in principle. Sample thin sections vertical to bedding were made of the coal (Zone 2), the black humulite (Zone 4), and the fine-bedded green humulite (Zone 6).

It was pointed out above (p. 105) that the classification of some of these deposits—as shale or as coal—depends on the point of view of the investigator. This is even more obvious in the case of the fresh-water sediments at Garrard Quarry. Zones 4 to 6 have all the typical features of shale except the microscopic composition; in the latter respect they are coals beyond doubt, consisting of brightly colored plant decomposition products with tremendous quantities of finely granular sulfides but no visible clay. We have chosen to call these unusual sediments "humulites" to indicate their similarity to true coal on the one hand and their physical appearance as shales on the other.

In the field the coal (Zone 2) may be split parallel to bedding. The split surfaces show flattened stems of all sizes, matted down in all directions. The stems appear to be separated from one another by thin layers of clay. Microscopic examination reveals the "clay" to be finely degraded red to orange plant particles very highly charged with sulfide granules. The stems themselves appear as anthraxylon bands lacking botanical structure.

In the black layer (Zone 4) stems are rare but there are quantities of small twigs and other brightly colored plant debris. All through this material there are large quantities of granular sulfide particles. There is no clay visible in the section. Shells of *Myalina* are not pyritic (as they are in Zones 5 and 6) and show columnar (perhaps original) shell structure. Skeletal debris of vertebrates is well preserved.

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[1] During the splitting of the shale and the charting of the fossil content of Mecca Quarry, the differences between these levels were nevertheless noteworthy, in terms of density of fossil debris, splittability, softness and bedding plane appearance of the various levels.

The microscopic structure of Zone 6 differs from that of Zone 4 in that the particles of plant debris are smaller and the sulfide granules are primarily placed in narrowly spaced, horizontal sheets (the finely divided sulfide forming green bedding surfaces). This is apparently the reason why this zone may be split into large, flexible sheets no more than a millimeter in thickness.

Comparison of the three zones (2, 4, and 6) thus shows differences in the size of the plant debris; in all other respects the sections are essentially identical. The extremely even cleavage in Zone 6, on planes of finely divided sulfide, results from the very great degree of comminution of the plant debris. In contrast to the black levels of the transgressive Mecca and Logan Quarry shales there is no clay and no material similar to micrinite.

3. *PLANT DECOMPOSITION PRODUCTS IN MODERN BLACK MUDS*

Coal petrologists have apparently never concerned themselves with black carbonaceous shales; hence there is no literature dealing with the nature and mode of origin of the microscopic components that make up such shales. As related to various kinds of coal the problem has led to a spirited discussion that seems to be continuing. A good summary of the status of present thinking is given by Marshall (1955).

Current knowledge of the microscopic composition of coals, the nature of the component parts, and their origin is almost entirely based on the study of high grade, economically important fuel and on technically useful special varieties. While this procedure was understandably dictated by economic considerations, it appears unfortunate, since deposits of this type present situations of far greater complexity than do poor grade coals and carbonaceous shales. Small wonder that an intensive debate has ensued concerning the classification of coals and their microscopic constituents as well as their nature and mode of origin. Broad differences of opinion exist, for example, concerning micrinite. Stach (1932) interpreted opaque flakes, which in his slides appeared to show a relationship to small spores, as substances precipitated out of solution. Kühlwein (1931) and Hacquebard (1952) considered similar structures as particulate plant degradation debris.

Our observations on modern black muds and on the character of plant decomposition products in the Mecca and Logan Quarry shales may throw further light on the subject.

a. MODERN BLACK MUD ENVIRONMENTS IN LOUISIANA: In order to gain some insight into the nature and significance of the microscopic components of the Mecca Quarry shale, we felt that first-hand experience with modern black mud deposits would be helpful. Accordingly, we devoted the 1956 field season to a trip to southern Louisiana, where black mud is being deposited at the present in many bayous, lakes and ponds. The area that we most often visited lies west of New Orleans off the southwest corner of Lake Pontchartrain. It is covered by an extensive cypress swamp which is drained by a number of bayous, such as Bayou Labranche and its tributary, Bayou Trépagnier. A short distance west of Bayou Labranche, which enters Lake Pontchartrain next to the eastern levee of the Bonnet Carré spillway (fig. 26, pl. 14, B), there is an area of swamp locally known as the Sarpi Wildlife Refuge, where deep ditches were dug some years ago by an oil company. Chicot Lagoon near Chef Menteur at the eastern end of Lake Pontchartrain was also visited, and, somewhat farther afield, Lake Hatch south of Houma, Louisiana. One of the objectives was to obtain samples of the black or dark gray muds that have accumulated in these situations, in order to determine the character of the partially decomposed plant remains that form a large part of these muds. The preservation of the mud samples is described (see p. 20).

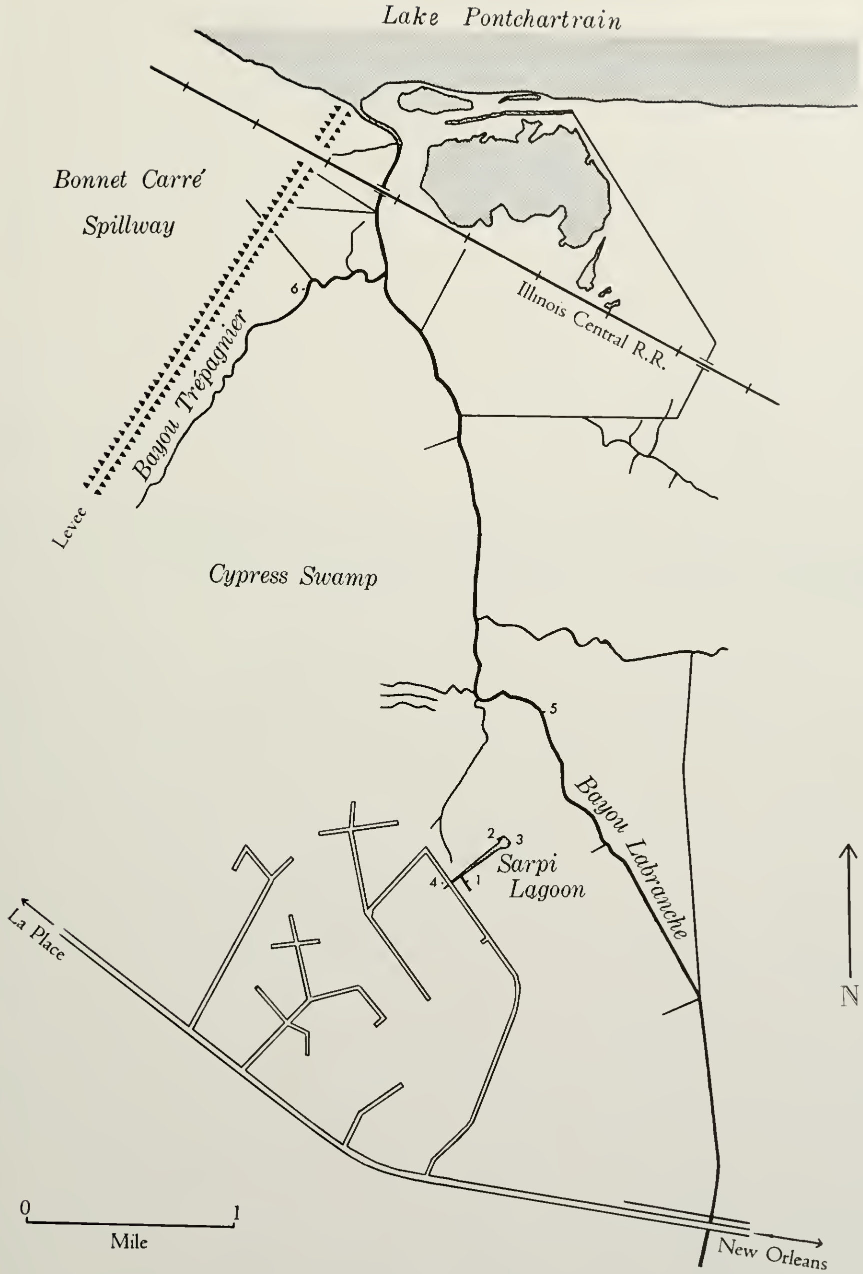
Lake Pontchartrain
Bonnet Carré
Spillway
Illinois Central R.R.
Bayou Trépagnier
Levee
6
Cypress Swamp
5
Bayou Labranche
2
3
4
1
Sarpi
Lagoon
La Place
N
0
1
Mile
New Orleans

Fig. 26. Map of Bayou Labranche and vicinity on southwest shore of Lake Pontchartrain, Louisiana. Numbers indicate field stations for observation of rates of fish decomposition as listed in Tables 6 and 9. Map drawn from aerial photograph.

Table 6.—BLACK MUD LOCALITIES IN LOUISIANA

Date 1956	Station	Locality	Water Depth	Sample		Sediment Character	pH	Temperature C.	Salinity %
				Surface,	Core				
July 7	6	Bayou Trépagnier	±4 feet	X		black mud	7	—	—
July 11	6	Bayou Trépagnier	±6 inches	—	X	black mud	7	34.4°	6.4
July 9	1	Sarpi Bayou	+16–20 inches	—	X	black mud	—	24.5°	2.5
July 21	1	Sarpi Bayou	—	—	—	black mud	6	26.8°	2.8
July 10	2	Sarpi Bayou cattail swamp	10 inches	—	X	gray clay	—	24.7°	3.4
July 10	3	cattail swamp small pond	4 feet	—	—	black mud	7	—	—
July 10	4	small pond near well 7	3 feet	—	—	black mud	—	24.5°	3.3
July 11	5	Bayou Labranche	±2 feet	X	—	"vegetable soup"	7	28.3°	3.2
July 13	7	Chicot Lagoon	1 foot	X	—	gray mud	6	37°	8.5
July 20	7	Chicot Lagoon	2 feet	—	—	gray mud	6	31°	5.9

In the following, the principal situations visited may be briefly described as regards their general character. Bayou Labranche (pl. 14, B), north of highway U.S. 61, is an enlarged natural drainageway through fairly solid cypress swamp. Part of its course is straight and may have been corrected in the past; little evidence of this is visible, however. The surrounding country is slightly higher than the water level of the bayou, and after a heavy rain, water may be seen running into the bayou all along its margins. Here and there along the margins and especially near the mouths of small tributaries there are floating mats of water hyacinth and alligator weed. The main body of the bayou was free of such vegetation at the time of our visits. Up to about two feet from the water surface, the channel is filled with a black mud to a depth of ten or more feet. The uppermost portion of this mud consists of partly decomposed vegetation debris that floats freely and its consistency can best be compared with that of minestra, a famous Italian vegetable soup. Farther down in the mud profile the debris becomes progressively finer and interstitial water decreases.

Some time prior to our visit, Bayou Labranche had become polluted by oil from a nearby refinery. Traces of this were still visible, but the effects of pollution on the particular observations that we intended to make were surely negligible. Sarpi Wildlife Refuge (fig. 26) is a producing oil field. At the time of its development a system of fairly deep ditches was dug in order to drain roadways for access to the well sites. One of these artificial bayous, henceforth referred to as Sarpi Bayou, extends northeast from well 7. Several stations were established in the vicinity of this bayou. The area, although it was no doubt severely disturbed at the time of the development of the field, has now an entirely natural appearance (except of course in regard to the layout of the ditches) and there is no visible trace of pollution. The bayous are essentially stagnant bodies of water containing black mud sometimes to near the surface, in much the same fashion as Bayou Labranche. At the eastern end of Sarpi Bayou there is a cattail swamp and near the southeastern margin of this there is a small pond, 4–5 feet deep. This contains a black, smelly mud, indicating reducing conditions. Directly in the vicinity of well 7 there is another ditch which was entirely covered with a lush mat of water hyacinth and alligator weed, so that the water was not visible (pl. 14, A).

Bayou Trépagnier (fig. 26) is a small tributary of Bayou Labranche. At the time of our visit it was notable because of the high water temperature (July 11, 1956, afternoon temperature 34.5° C., sediment temperature 33.2° C.) and the foul smell of the water as well as of the sediment.

Chicot Lagoon is a shallow basin enclosed by marsh grasses and connected with the Intracoastal Waterway by a narrow channel. Much of the bottom of Chicot Lagoon is above water at low tide and the depth of the basin varies somewhat; during low tide it is from 2 to 3 feet deep. On the bottom is a soft gray mud barely capable of supporting a man wading through it. Its water temperature is very high (July 13, 1956, afternoon temperature 37.2° C.). During both visits made to this site we were impressed by the fantastic number of fishes in the lagoon. They were jumping all around the boat.

Lake Hatch (see Russell, 1942) lies south of the town of Houma, Louisiana. The lake is covered, all around its margin, by what is descriptively called a *flotant* by the local people—a mat of floating vegetation up to three feet thick near the margin and thinning gradually toward the center of the lake until it is merely a fringe of water hyacinth and alligator weed. Beyond this there is a small area of open water. It is possible to walk out onto the *flotant* for a considerable distance. The mud below it is about 10 feet deep (down to firm, light blue clay, 20–22 feet according to Russell). An iron pipe lowered vertically through the *flotant* penetrated under its own weight 6 or 7 feet and could be sunk another 3 or 4 feet with slight pressure. The rate of sedimentation of plant decomposition products below a *flotant* is evidently very great, but there is as yet little useful information on this point.

b. THE MICROSCOPIC CHARACTER OF THE PLANT DECOMPOSITION PRODUCTS: The muds obtained from the mentioned localities have one feature in common: the decomposition products of vegetable origin are of two kinds that are intermixed, namely, entirely opaque plant debris and translucent debris which is usually brown to reddish brown in color in transmitted light and which shows various morphological features, such as cell walls and vascular bundles. There would seem to be no doubt that these very different types of decomposition products, opaques and browns, are formed in the same general environment, probably at the same time. Since debris of both types floats intermingled for some time near the top of the mud column, subject to the same macro- and microenvironmental conditions, it would appear highly probable that the factors that initiated each type of decomposition were of varied sort at the very beginning of the decomposition process. What happens thereafter requires detailed investigation. Our observations tend to indicate merely further reduction of particle size in both types of decomposition products.

The opaque particles in the mud samples fall into three classes: plant debris with opaque cell walls and clear cell spaces; entirely opaque rods and flakes devoid of botanical structure; and particles that look like charcoal (pl. 15, A and B). In microscopic appearance the opaque material in the Mecca Quarry shale is all but identical with the last two kinds of debris mentioned. There is, indeed, a startling overall similarity between the microscopic appearance of bayou mud samples and horizontal sections through Mecca Quarry shale (cf. pls. 10, H and I, and 15). The indication that there might be little difference between the plant particles in the modern and ancient muds is intriguing. This idea is admittedly unorthodox, and mere similarity in appearance may be misleading. But there is other evidence that seems to point in the same direction, namely, the nature and position of fossil inclusions such as sticks (p. 107); the rapid rate of deposition (p. 175); and the large amounts of trace elements (p. 97)—all indicating relatively little diagenetic alteration of the shale.

In order to gain some insight into the process of plant decomposition that leads to opaque debris, we collected quantities of leaves from the surface of the mud column along the edges of the bayous, and dried them immediately between blotting paper. Many of these leaves were partially macerated, brown or gray in color; others were deep black. The black gum (*Nyssa*) leaf (pl. 16, A) shows the beginning stages of maceration. The veins of all sizes have become completely opaque (pls. 16, B, and 17, B) but some of the tissue within the areas bounded by the smallest veinlets is dull-brown, as in the illustrated *Salix* leaf (pl. 17, A). The opaque veinlets look identical with the rod-like opaque elements in the mud samples (and similar elements in the shale). Some leaves were entirely black on the surface and showed no obvious signs of tissue maceration. A number of leaves of this appearance were cross sectioned with the microtome, which furnished rather interesting evidence. In these leaves the process of decomposition had evidently just begun. The tissues show no undue alterations except near the surfaces where the cells are opaque (pls. 18, A, and 19, A, B). On high magnification (pl. 19, B) it may be noted that the cell content has become opaque, whereas the cell walls remain translucent. This is particularly well seen on the right side of the picture where two guard cells are visible, with the included stomate. In another leaf section (pls. 18, C, and 19, A) deeper leaf cells have become opaque, and in still others the entire leaf thickness has become an almost solid black mass save for the vein, which has remained clear (pls. 18, B, and 19, C).

This evidence would indicate that opaque substances develop early in the decomposition process, soon after death of the plant tissue and even before maceration. The process may affect different parts of the plant, but it appears to involve the surface cells first, gradually progressing toward the deeper tissues. Obviously, however, opaque matter does not form in all decomposing leaves. The question thus arises as to the specific conditions under which opaque substances develop, or, conversely, do not develop.

Numerous field observations suggest the general conditions under which opaque material forms. In the ravines of Parke County, which are covered by deciduous forest, dead leaves turn black in situations where they remain wet, though exposed to the air. Straw piled a foot thick in wet places will turn black in and near the water surface in the course of five winter months (in the Chicago area) but not near the surface of the pile where it is exposed to the air and is dry most of the time. Moisture and good aeration both seem to be prerequisites.

In summary, it may be stated that plant decomposition products of modern black mud situations such as those studied in southern Louisiana are of two kinds, translucent (brown in color) and opaque. These are intermixed in the mud. It is probable that decomposition resulting in opaque products starts early in the process and requires both high moisture and aeration. The exact conditions remain to be investigated.

4. *ORIGIN OF MICROSCOPIC COMPONENTS OF MECCA AND LOGAN QUARRY SHALES*

a. CLAY: Clay occurs throughout the Mecca and Logan Quarry shale profiles but the amounts vary greatly. There is an increase in the quantity of clay in alternate levels, most clearly seen in the Logan Quarry sequence (see fig. 25). In the Mecca Quarry profile the alternation is better illustrated by the shale reflectivity curve (fig. 5). An alternation of gray and black levels was also observed in all other localities in Parke County and vicinity. Clay thus shows a pattern of periodic abundance throughout the sequence of the Mecca Quarry shale. Since the black shale profile overlies a coal that does not contain clay bands (except for one parting; see p. 206) we must presume that the factors responsible for the clay deposition in this area did not exist during the time of peat accumulation and, once they had come into play, were of a periodic nature. Since the overall sequence of beds from underclay to a marine limestone in each case clearly indicates a marine transgression over a low coastal plain, the question of origin of the clay may well be a complicated one.

1. *Sea-borne Clay:* Although there is good evidence to suppose that this transgression was a very gradual process, for the most part leaving no indications of violence, one cannot rule out the possibility that some of the shore muds were stirred up by wave action and carried inland some distance to be redeposited. Such deposits would probably contain bits of broken shells of marine organisms, occasionally even whole shells. In the Mecca Quarry shale sequence there is such a level, the transgression shell breccia (see p. 32), which directly overlies the coal. The clay of level M at Logan Quarry, containing marine invertebrates, was probably likewise washed in from the sea.

2. *Stream-borne Clay:* The sheety gray levels above the transgression shell breccia contain very few shells of invertebrates, mostly cephalopods (see p. 151), and no shell debris except for shells that have been chewed by predators (see p. 138). There are no pelecypods and no productid brachiopods, though they were very plentiful in the nearby marine environment (see p. 94). This evidence alone suggests that these clays were deposited in an environment unfavorable for such strictly marine animals as the pectinoids and the productids. The periodicity of major clay deposition in the shale sequence above the transgression shell breccia suggests, in this case, seasonal changes (see rate of deposition, p. 175) that resemble the alternation between rainy and dry seasons of modern subtropical climates. It is furthermore significant that the sheety gray levels are consistently thicker in the Logan Quarry shale than in the Mecca Quarry shale. The physiographic zone repsented by the outcrop belt of the former lies landward of that of the Mecca Quarry shale (p. 227). All these considerations lead to the conclusion that the clay in the sheety gray levels originated in the hinterland of the coastal plain and was borne by flooding drainage systems.

3. *Air-borne Clay:* It may well be that some of the clay was deposited as air-borne dust. We have no evidence that would either indicate or exclude the possibility of this mode of clay transportation. The vast amounts of clay sediments in the Illinois Basin would certainly suggest active erosion and consequently denudation in the higher hinterland of the coastal belt around the epicontinental sea, and it is not inconceivable that dust storms might have transported some of the clay in the black shale levels that seem to reflect dry periods.

In conclusion, it appears that the clay in the Mecca Quarry shale is of two different origins: first primarily sea-borne in the transgression shell breccia, thereafter mostly stream-borne until the area was sufficiently below sea level to permit the establishment of a normal marine environment of deposition.

b. Plant Decomposition Products: Macroscopic plant decomposition products in the Mecca Quarry shale consist primarily of driftwood logs, sticks, and twigs of all sizes, which are carbonized, or often no more than a thin band of conchoidally fracturing bitumen or anthraxylon (similar in appearance to pitch) with a longitudinally striated surface. Rarely are nodes seen, and even more rarely pieces of recognizable bark. Sand grains are often attached to the surfaces of such sticks. In microscopic section these sticks appear as well-defined, dull to bright orange-red elements. In all of the shale examined in the charting of the fossil content of the Mecca Quarry (see p. 10) only two leaflets of *Neuropteris* were seen and collected. The veinlet pattern of these leaves left sharp impressions in the shale and the leaf areas are shiny in contrast to the dull shale surface nearby. In addition, two specimens of very different size were tentatively identified as possible megaspores, and their mode of preservation is much the same as that of driftwood. In certain levels of the Mecca Quarry there are abundant "ghosts" of what we believe to have been seaweeds. These are light brown, exceedingly thin, apparently structureless remains probably of plant nature, that show a number of characteristic shapes (pl. 21, A).

These observations are of importance in the discussion of the origin of the vast amount of decomposition material of plant origin that is part of the Mecca Quarry shale. They prove that the conditions for recognizable preservation of plant material such as leaves, twigs, bark and possible seaweed were present, and that their scarcity is due to factors other than unfavorable conditions for preservation. For these reasons and the presence of sand on many sticks, which is not otherwise found in the shale, we may reasonably assume that these elements had floated into the Mecca and Logan Quarry environments from elsewhere.

This, then, poses the problem of the source of the bulk of the plant-derived material in the shale. If it had been washed in from nearby stands of coal forest, we should expect a larger number of leaves and twigs to have been preserved in recognizable condition. If it were redeposited material from eroded peat accumulations some distance away, one would probably have to assume current velocity of sufficient magnitude to carry large quantities of such debris in a short time. As set forth in the section on particle orientation (p. 156), there is no evidence of currents (except very minimal in level C) strong enough to orient a light and ideally suited particle such as a *Listracanthus* spine, or sticks and twigs. It should also be remembered that black shales cover enormous areas, often extending far beyond the underlying coal seams, and that the coal surfaces do not show any signs of erosion. The supposition that the plant material originated elsewhere and was transported to the Mecca and Logan environments meets with so many difficulties that it must be ruled out as a possibility.

There remains the possibility that the plants grew, died, and decayed in the Mecca and Logan areas. Peat deposition was terminated in this area with the initial thrust of the marine waters through the coal forest. The trees that lived there at that moment lie on top of the coal seam as recognizable, heavily pyritized logs, only modestly compressed. It is thus not reasonable to assume that anything like a coal forest community produced the plant debris of the shale. Very likely there existed aquatic plant communities in the Pennsylvanian as there do today. In the absence of either positive or negative evidence it may be admissible to assume that they occupied ecological niches similar to those of the modern plants, growing wholly submerged and rooted in the bottom sediment (Moore, 1929) or floating near or on the water surface.

The almost perfectly even-bedded character of the shale, splitting over large areas into sheets no thicker than ordinary cardboard, makes it seem unlikely that plants actually rooted in the sediment. If such had been the case one would expect a far greater number of recognizable plant impressions and a greater disturbance of the bedding. Furthermore, a shallow open body of water with a bottom consisting of a fine-grained loose sediment does not produce an even-bedded, virtually undisturbed sediment. The slightest wave action caused by wind or tide stirs up the bottom mud of Lake Pontchartrain (Darnell, 1958, and our own observations). The mode of preservation of the fossils (see p. 128) in the Mecca Quarry shale shows no evidence of any disturbance whatsoever of the bottom mud at the time of its accumulation. For these reasons it seems to us probable that the Mecca and Logan Quarry environments were covered by a floating mat of vegetation, a *flotant* (Russell, 1942), similar perhaps to those presently widespread in southern Louisiana and no doubt elsewhere along the Gulf Coast.[1] According to Russell it takes the wind force of a hurricane to disrupt a well-established *flotant.* Under ordinary conditions the depositional environment underneath a *flotant* is extremely quiet and undisturbed. Also, the constant growth of vegetation above and the decay at the bottom of the floating mattress produces a constant and large amount of plant debris.

The protection of the depositional environment from wave action and the constant production of large quantities of plant decomposition products are the two principal reasons for the postulation of a *flotant* in the Mecca area during the deposition of the black shale sequence. There are others. The large shark (pls. 24 and 25) discovered at Logan Quarry has the denticles of the skin (shagreen) perfectly in place. Immediately above this specimen there is the upper black band of level J described above (p. 69). The most likely explanation is to the effect that the pool in which that shark perished actually dried up (for evidence of this see p. 136) under the *flotant,* which matted over the bottom mud and the carcass, holding it in place perfectly, even after the subsequent rising of the water level.

We have no evidence as to the nature of the plant community of such a *flotant.* If it had consisted of leafy plants, one probably would expect occasional impressions of their leaves, which is not the case; but if the *flotant* consisted of a layer of, for example, algae, one could hardly expect these to be recognizable after decomposition.

Postulation of an algal *flotant* over the Mecca and Logan areas explains a number of other aspects of the Mecca Quarry shale that are otherwise difficult to understand. The notable scarcity of spores in the shale, and the absence of insect remains in a sediment capable of preserving such delicate animals as oligochaete worms (pl. 21, C) cannot reasonably be explained by assuming that these elements were either not present in the area or not preservable. A floating algal mat, on the other hand, would have prevented their inclusion in the bottom mud prior to decomposition.

There is, furthermore, the question of oxygenation of the water. A shallow, nearly stagnant body of water in which vast quantities of organic material are decomposed at a rapid rate should be expected to become deoxygenated in a short time. In addition there was a high concentration of fishes (see p. 191) also consuming oxygen. Yet there is no evidence that the fishes died of asphyxiation or poisoning (see p. 134) and there is no evidence that most of the animals were exterminated at any time during the deposition of the Mecca and Logan Quarry shales (see fig. 32, vertical distribution, Mecca Quarry shale). This indicates beyond doubt that the water was sufficiently aerated to permit survival of a dense concentration of animals. It may be argued, of course, that air is going into solution at the surface continually and that this might be sufficient to permit the fishes to survive. Would it be enough, however, for the opaque decomposition of the bulk of the plant material? Such decomposition is generally thought to take place under aerated conditions (p. 118, and Hacquebard, 1952). A vigorous growth of algae near the surface of the water, on the other hand, would produce notable quantities of oxygen which would not only aerate the surface water but would provide the proper conditions on the under side of the *flotant* for the opaque decomposition of the dead vegetation (see also p. 119). Conditions at the bottom were nearly anaerobic, as is shown by the differential mode of decomposition (under side versus upper side) of shark carcasses (p. 173).

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[1] The idea of deposition of black shale beneath *flotant*-covered shallow water has been approached by others, though not, to our knowledge, fully examined. Leo Lesquereux (1857, pp. 508–509, 518) verged on this concept.

G. THE FOSSIL CONTENT OF THE MECCA AND LOGAN QUARRY SHALES

1. *FLORA AND FAUNA*

Systematic studies of the flora and fauna of the Mecca and Logan Quarry shales have not yet been made. The forms that could readily be identified are listed by name, but even these require further study.

The following listing provides only an overall impression of the character of the assemblages and of the relative abundance of the various elements.

Systematic study of the flora and fauna is planned to follow after publication of the present account.

The following abbreviations will be used below:

GQ: Garrard Quarry
LQ: Logan Quarry
LQS: Logan Quarry shale
MQ: Mecca Quarry
MQS: Mecca Quarry shale
TSB: transgression shell breccia

FLORA

Identifiable plant remains are extremely rare in the transgressive sheety shales (see p. 126). The following list includes such floral elements as we have noticed:

Neuropteris sp. One isolated pinnule apiece in levels A1 and B1 (MQ).

Sphenopteris sp. A fair number of pinnules and parts of pinnae (GQ, Zone 6; pl. 21, B).

Pecopteris sp. A fair number of pinnules and parts of pinnae (GQ, Zone 6).

Omphalophloios cyclostigma (Lesquereux). One piece with recognizable pattern (MQ, level B4.1; pl. 20, B).

Syringodendron sp. One piece of a stem (MQ, level B3.3).

Calamites sp. Several pieces of stem (MQ, level B1.2, level D; LQ, one in each of levels G, H, K; pl. 20, D); pieces in gray levels larger than in black.

Driftwood, indet. In fair abundance in all transgressive sheety shales and in the humulites (pl. 20, A).

"Seaweeds." These are structureless light to dark brown smudges on the bedding planes of black sheety shales, often displaying characteristic patterns (pl. 21, A). Our reason for calling these remains "seaweeds" is their similarity in preservation to a specimen from the Kanizer coal mine, near Clinton, Indiana, which resembles perfectly in shape, size and branching characteristics a herbarium specimen of *Codium*, a modern marine green alga. Several well-organized forms with recognizable pattern occur throughout level A3 (MQ) but most abundantly at the bottom of level A3.1, and sporadically elsewhere.

Another type, consisting of groups of small, circular, brown marks, occurs in the "A-plus" level (MQS) at Montgomery Creek and in the sheety shale (MQS) at the Arketex and West Montezuma clay pits.

Plant degradation products. These are a notable constituent of the sheety shales and humulites (see p. 119). Among them there are, in all levels of the sheety shale and also in the channel clod, good-sized pieces of fusain. Spores are present in the shale, but are not common.

FAUNA

INVERTEBRATES

Porifera indet. Small, flat, circular patches of spicules, rare; MQ, levels B and D; LQS, isolated pyritic spicules, Dosdange Creek, level J.

Coelenterata

Lophophyllidium proliferum (McChesney). MQS, channel clod, fairly common; IIA shale, channel clod, Coal Creek, common.

Bryozoa

Arborescent forms, not identified, several species. MQS, channel clod, fairly common; sheety shale above Coal III, Hanging Rock, fairly common.

Brachiopoda

Inarticulata

Lingula, cf. *L. mytiloides* Sowerby. MQ, levels D to B3 (a few); LQS, Haworth Creek, *Myalina* zone (common), *Dunbarella* zone (fairly common); GQ, top of Zone 6 (common), Zone 7 (fairly common).

Orbiculoid brachiopods, at least two species. MQ, level D (not common), levels B4 (not common), and B1.3 (rare), not observed above level A4; LQ, levels J (rare) and G (rare); LQS, Haworth Creek, *Dunbarella* zone (moderately common); Trumpet Valley, level J; Newport, present; GQ, Zone 6 (rare; a different species from that at MQ); Coal Creek, base of IIA shale, present.

Articulata

Desmoinesia muricatina (Norwood and Pratten). MQS, channel clod and TSB (very abundant).

Mesolobus mesolobus (Norwood and Pratten), varieties *mesolobus* (Norwood and Pratten) and *euampygus* (Girty). MQS, channel clod (fairly common, valves together); LQS, Haworth Creek, *Dunbarella* zone (common).

Antiquatonia portlockiana (Norwood and Pratten). IIA black shale, channel clod, Coal Creek (fairly common).

Productid spine. MQ, level D (one).

Composita subtilita (Hall). MQS, channel clod (fairly common); IIA black shale, channel clod, Coal Creek.

Neospirifer sp. MQS, channel clod (fairly common); IIA shale, channel clod, Coal Creek.

Wellerella sp. LQ, level G (one); LQS, Haworth Creek, *Dunbarella* zone (rare).

Mollusca

Gastropoda

The TSB contains a large fauna of gastropods, including the following forms: pseudozygopleurids, *Palaeostylus* sp., *Meekospira peracuta, Soleniscus* sp., *Glabrocingulum* sp., *Ananias* sp., *Girtyspira?* sp., *Pharkidonotus percarinatus.*

Pseudozygopleurids and juvenile bellerophontids were seen in the *Dunbarella* zone and cephalopod zone (LQS) at Haworth Creek.

Phanerotrema sp. LQS, GQ, Zone 9.

Small gastropod, indet. LQS, GQ, Zones 4–6.

Cephalopoda

Nautiloidea

Pseudorthoceras knoxense (McChesney). Present everywhere in MQS and LQS (though not in the humulite facies), nowhere in abundance; IIA shale, channel clod, Coal Creek; black shale above Coal III, Hanging Rock.

Pseudorthoceratid with longitudinal ornament. MQ (one).

Very large straight nautiloid, indet. MQ (rare).

Coiled nautiloids, indet. MQ, TSB (fragments common), levels D to A (rare); LQ, black levels (rare); LQS, GQ, Zone 9; Haworth Creek, *Dunbarella* zone and cephalopod zone (rare); IIA black shale and channel clod, Coal Creek (rare).

Giant coiled nautiloid, indet. LQ, levels F (common) and G (rare).

Ammonoidea

Goniatites

Pronorites arkansasensis (Smith).

Paralegoceras cf. *P. iowense* (Meek and Worthen).

These forms are fairly common in LQ, level G.

Goniatite, indet. LQS, level Kb, South Collings Creek.

Pelecypoda

Myalina (*Myalinella*) *meeki* Dunbar. MQ, levels D to B2 (rare); MQS, Arketex (rare); LQS, GQ, Zones 4, 5, 6 (very abundant in Zones 4 and 5); *Myalina* zone, Haworth Creek (locally very common); in humulites of LQS elsewhere; sheety shale over Coal III, Hanging Rock.

Dunbarella sp. MQ, level D (very abundant); MQS, in basal level (D) generally, but not equally abundant everywhere; MQ, in TSB (not common); LQ, fragments in level M, numerous fragments and rare whole shells in level Kb; LQS, GQ, very abundant in Zones 7 and 8, rare at top of Zone 6 and in Zone 9; very abundant at Big Pond Creek; very abundant in *Dunbarella* through cephalopod zones at Haworth Creek; less common in basal black sheety shales everywhere.

Euchondria sp. LQS, *Dunbarella* and cephalopod zones, Haworth Creek (rare).

Streblochondria tenuilineata (Meek and Worthen). LQS, *Dunbarella* zone, Haworth Creek (rare).

Pteria sp. LQS, *Pteria* and *Dunbarella* zones, Haworth Creek (very common), Big Pond Creek (very common).

Pteriid, indet. LQS, Big Pond Creek; *Dunbarella* zone, Haworth Creek (rare).

Nucula, cf. *N. parva* McChesney. MQS, TSB, Montgomery Creek (rare).

Edmondia sp. MQS, TSB, Montgomery Creek (rare); LQS, GQ, zones 7, 8 (rare); *Pteria* zone, Haworth Creek (rare).

Allorisma subcuneata Meek and Hayden. MQS, TSB, Montgomery Creek (rare).

Worms

Annelida

Polychaeta Tubicola

Microconchus sp. MQ, level D (fairly common); LQ, level Kb (fairly common); LQS, Big Pond Creek and Haworth Creek (common); GQ, Zone 4 (not common); IIA shale, channel clod, Coal Creek.

Serpulid, indet. MQ, level D (rare); MQS, Barren Creek (rare); LQS, *Dunbarella* and cephalopod zones, Haworth Creek (not common); IIA shale, Coal Creek (present); occurs in very large numbers in LQ limestone.

Oligochaeta

Oligochaete, indet. MQ, level B1 (two individuals; one illustrated on pl. 21, C).

Worm fecal casts. LQ, level G (locally in vast numbers).

Worm trails. MQ, levels D and ?B2; LQ, level G (single specimen); LQS, level F?, Dosdange Creek (present); IIA shale, Coal Creek (present).

Arthropoda

Trilobita

Brachymetopus sp. MQS, channel clod, West Montezuma (single specimen).

Crustacea

Ostracoda, indet. LQS, GQ, Zones 3 and 4 (fairly common); fresh-water profile beneath LQ coal, Newport and Woodland Valley (see sections, pp. 78, 81) (coquinite); LQ, in coal (two specimens); black sheety shale above Coal III, Hanging Rock.

Phyllocarida

Concavicaris sinuata (Meek). MQ, abundant in levels B2.1 and A3.4 (see fig. 32; pl. 22, A–C); elsewhere in MQS less common; LQ, level G (8 specimens).

Percarida, indet. LQS, GQ, Zones 5 and 6 (fairly common); *Myalina* zone, Haworth Creek; humulite generally.

Echinodermata

Crinoids, indet. MQ, TSB; MQS, channel clod (rare); LQ, level J, one specimen of a gastric residue contains crinoid columnals and calyx plates; IIA shale, channel clod, Coal Creek.

Conodonts. MQ and MQS, common in sheety shales; LQ, none; LQS, cephalopod zone, Haworth Creek (common); level J, Dosdange Creek (present); shale above Coal III, Hanging Rock (present).

Problematica: A number of problematical remains are noted in MQS and LQS (none common).

VERTEBRATES

The vertebrate remains are found primarily in the transgressive sheety shales in the area under study. Their abundance varies within wide limits; at Barren Creek, for example, save for a few fragments, no vertebrate remains are encountered in either MQS or LQS, in spite of excellent exposures. MQ contains the maximum burial density of vertebrates (see p. 191); LQ and GQ contain a smaller concentration of remains; within the limits of GQ, the density varies from zero to notable (see fig. 17).

Acanthodi

Acanthodes? sp. MQ and MQS (fairly common); LQ, level J (common), G (rare); LQS, GQ, Zones 5 and 7 or 8 (rare); elsewhere, present.

"Placoderms."[1] MQ (common); MQS, present at most localities, notably so at West Montezuma; LQ (rare); LQS, present but rare.

Elasmobranchii. At least a dozen genera are present at MQ and LQ, and elsewhere in the shales; the relative abundance of the different species, however, varies greatly in different microstratigraphic levels, megastratigraphic horizons, and localities. *Petrodus* and *Listracanthus*, for example, are very common at MQ (see fig. 32) but exceedingly rare at LQ.

Teeth of a pleuracanthid. LQS, GQ, levels 4 to 6 (fairly common).

Palaeoniscoidea. At least two large forms occur abundantly in the MQS and LQS (except in the humulites); a number of small forms are restricted to the humulite facies, LQS.

Crossopterygia

?Rhipidistian. LQS, GQ, levels 4 to 6, isolated bones, teeth and scales (fairly common).

2. *THE CONDITION OF THE FOSSIL CONTENT*

a. GENERAL

Plants, invertebrates and vertebrates are not equally well preserved in the Mecca and Logan Quarry shales. The plant tissues were, for the most part, degraded to microscopic particles (see p. 105) that form an integral part of the shale, or were changed into carbonized films of leaves (Garrard Quarry) or, in the case of logs, into bright, vitrain-like substances.

The mode of preservation of the invertebrates varies somewhat with the species and sometimes with the individual. In general the phosphatic shell material is primary. The aragonitic shells may be replaced (see below). Deformation of thin shell material is the rule. Pyritized specimens occur in certain localities and levels.

Pyritized pelecypods appear to be a good indicator of the relative stagnancy of the water and probably of the presence of large quantities of decomposing proteins in the immediate environment of deposition. This is beautifully demonstrated in the sequence of beds that follows deposition of the coal at Garrard Quarry. Zone 4 is dense, waxy, unevenly bedded, black humulite that contains countless non-pyritic fragments (and occasionally whole shells) of *Myalina* (*Myalinella*) *meeki*. This zone grades into Zone 5, which is olive-green in appearance but otherwise has retained all the above-mentioned characteristics. Here the *Myalina* shells are pyritic; they decrease drastically in numbers in the green, perfectly even-bedded Zone 6 above (see Garrard Quarry profile, p. 69). In Zones 7 (olive-green in color) and 8 (gray in color), representing the marine facies, *Dunbarella* in very large numbers are pyritic even though the shale (while still containing pyrite) is no longer green and some amount of circulation must have been re-established at the time of deposition. In Zone 9 the shale is dense and black and such specimens of *Dunbarella* as do occur in this level are not pyritic. The Garrard Quarry sequence thus contains a splendid record of a body of water becoming stagnant, remaining stagnant for some time and then gradually becoming aerated again. The pelecypods reflect this history by being pyritic from the base of Zone 5 to the base of Zone 9—not merely during deposition of Zone 6, which represents the extreme conditions of stagnancy of the bottom waters.

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[1] The term "placoderm" for these animals is used in the broad sense of Romer (1945); their systematic position remains to be determined. They are animals of overall tadpole habitus, with a calcified cartilage skeleton and a set of presumably dermal bones and elements consisting of dentine. The possibility that they might be primitive (though aberrant) elasmobranchs cannot be ruled out.

In contrast to the pelecypods, no pyritized specimens of either linguloid or orbiculoid brachiopods have been noted in the Mecca Quarry and Logan Quarry shales, even where they occur side by side with pyritized pelecypods, as in the extremely pyritic Zone 6 of Garrard Quarry. These brachiopods thus agree in this regard with the vertebrates, which are never pyritized in the Mecca and Logan Quarry shales.[1] The reason for this phenomenon very probably lies in the different chemical composition of the hard parts of these animals. Linguloid and orbiculoid brachiopods and vertebrates have notable amounts of phosphates in their skeletons; the pelecypods lack phosphates.

The hard parts of vertebrates (bone, dentine, calcified cartilage) are generally very well preserved, with nearly perfect microscopic structural detail and little mineral alteration. Individual elements show very little or no evidence of deformation due to compression or collapse. Such defects as are commonly seen are attributable to different causes (see p. 130).

b. THE PLANTS OF THE MECCA AND LOGAN QUARRY SHALES

In the Mecca and Logan Quarry shales macroscopic evidence of plants consists almost exclusively of logs and sticks that have no recognizable botanical characters and consist of a shiny black material, red under transmitted light in thin section, similar to (or perhaps identical with) anthraxylon bands in bituminous coal. The surfaces of such logs are usually finely striated lengthwise, and sand grains are attached to many of them, though sand is never found in the surrounding sediment. Rarely, such sticks do show a morphological character such as the position of a node (pl. 20, D) or a vague pattern (pl. 20, B). Impressions of leaves are all but absent; only two were seen during the reduction of the Mecca Quarry, and these lack a carbonaceous film. None were noted at Logan Quarry.

In the fresh-water humulite of Garrard Quarry, leaf fragments are fairly common in Zone 6, preserved as carbonaceous films with good surface detail (pl. 21, B).

c. THE INVERTEBRATES IN THE MECCA AND LOGAN QUARRY SHALES

Cephalopods

The phragmocone of *Pseudorthoceras* with its heavy cameral deposits is almost always preserved uncrushed, but the flattened living chamber leaves merely a sharp impression in the shale and appears to have been partly dissolved prior to burial.

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[1] An occasional bone may be covered by a thin film of pyrite but the bone as such is not replaced by pyrite.

In all facies of the sheety black shale, the coiled cephalopods are flattened. The camerae are empty, the opposite walls lying in contact in the flattened condition. Between the walls of the living chamber is only a thin film of shale, indicating that the cavity was occupied during sedimentation by the rapidly decaying soft parts of the animal. The condition of preservation of these shells is of considerable interest. Commonly, in other deposits where cephalopod shells were buried in fine-grained sediments, mud filled not only the living chamber, but, penetrating through the siphuncle, filled also the camerae posterior to it. The lack of filling in the living chambers in the Mecca and Logan Quarry shales points to rapid deposition of the black mud. Furthermore, it is probable that the flaky nature of the organic debris in the sediment prevented its penetrating the siphuncle. In view of the apparently rapid rate of solution of the aragonite shell, leading to its partial removal from around the living chamber of *Pseudorthoceras* before burial (pl. 22, F), it is probable that the shells of the coiled cephalopods had been rendered so weak by solution that their flattening in the shale is primarily the result of collapse rather than of crushing by superposed weight of sediment (see pp. 176–182, Compaction of Shale).

The large cephalopod shells are represented by a soft, rather spongy, limonitic calcite, undoubtedly a secondary deposit replacing the original aragonite-calcite shell material. The goniatites, confined to level G in Logan Quarry, are principally empty molds with a minor amount of spongy calcite (pl. 22, G).

A suspected aptychus in Mecca Quarry, level A2.2, is a heavy structure of shape and dimensions such that it could have come from a coiled cephalopod of about 7 inches in diameter; a shell of this size was encountered only a short distance from the aptychus, and in virtually the same plane.

PELECYPODS

The pectinoid, *Dunbarella*, occurs in level D of Mecca Quarry as fine inner and outer impressions (pl. 22, D), some coated with pyrite. Neither the original shell substance nor a replacement mineral is usually present in this level. The shells are often finely wrinkled or shriveled, suggesting to us that the mineral matter might have been removed prior to burial, leaving only a thin periostracum to make an imprint. At some other localities (e.g., Big Pond Creek and Newport, in the Logan Quarry shale), *Dunbarella* was buried as entire individuals (pl. 24, A); hence the impressions are molds of the periostracum of the paired valves. Secondary calcite has filled the molds, spreading the impressions apart by as much as one eighth of an inch. At Garrard Quarry, *Dunbarella* is generally pyritic.

A pteriid, *Pteria*, occurs commonly with *Dunbarella*. Its mode of preservation is most unusual. In all cases, the hinge and the anterior halves of the valves occur as thin pyrite films or as impressions, the posterior half having been dissolved before burial (see pl. 22, H).

Myalina, a mytiloid, is most common in Zones 4 and 5 at Garrard Quarry. Its shell has color lines and prismatic structure, possibly the original shell material, in Zone 4; in Zone 5 it is completely pyritized.

WORMS

Calcareous tubes of a small elongated serpulid worm and of *Microconchus*, a small coiled serpulid, are preserved apparently unchanged in the Logan and Mecca Quarry shales. The elongated tubes occur either free[1] or attached to *Dunbarella* and other shells; *Microconchus* is always attached to shells.

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[1] These are particularly characteristic of the Logan Quarry limestone.

Two specimens of an oligochaete worm, represented as impressions of the bristle rows, were found in the Mecca Quarry, level B1 (see pl. 21, C).

Trails, questionably of worms, were found in levels B2 and D. Countless small wormlike fossils were found in a small area of level G at Logan Quarry. They consist of a light brown substance of fine texture, resembling fecal matter. They have the shape of contorted cylinders, transversely grooved or wrinkled.

Conodonts

Conodonts occur commonly in the Mecca Quarry as isolated, and relatively rarely as associated, jaw elements; they are white to rose-colored, presumably unaltered.

Inarticulate Brachiopods

Orbiculoid brachiopods and linguloids often have shell material preserved, the latter sometimes even with color markings (see pl. 23, C and D).

Crustaceans

In Zone 4, Garrard Quarry, isolated ostracode valves are preserved as thin secondary calcitic replacements. A few dubious impressions in the Logan Quarry coal at Logan Quarry, lacking shells, may represent ostracodes.

Percarid crustaceans are represented in Zones 5 and 6 at Garrard Quarry and elsewhere in the humulite, where they are preserved as bituminized replacements, usually intact, but in many cases consisting only of the terminal abdominal segments and uropods.

The most interesting crustacean in this fauna is *Concavicaris sinuata,* a moderate-sized phyllocarid. The test is phosphatic, commonly preserved as a buff to blue-gray to black material of several layers, with a characteristic surface ornament (pl. 22, A, B, C). Many of the tests are badly shriveled. Since it is difficult to understand how a calcareous-phosphatic carapace can shrivel, we offer the suggestion that these may represent freshly molted individuals, in the "soft-shell" stage. Alternatively, they may represent individuals eaten and regurgitated by predators, the mineral having been leached from the chitinous framework by stomach acids, though there is little evidence of such chemical action on bones and scales that have been regurgitated.

d. THE VERTEBRATES OF THE MECCA AND LOGAN QUARRY SHALES

Skeletal material of vertebrates is generally very well preserved and almost always draped over a single horizontal plane in the shale. In thin section bone and dentine show fine morphological structural detail, often emphasized by brown, probably colloidal precipitates, that must have been available at the time of deposition (p. 178). Sometimes teeth, bones and calcified cartilage have been (presumably) replaced by a very brittle substance, resembling a high rank hydrocarbon. This is particularly true of skeletal elements inside of some coprolites and of some specimens interpreted as gastric residues (see p. 102). Diagenetic de-mineralization and replacement were also noted (p. 141).

e. COMPLETENESS OF FOSSIL RECORD

The condition of preservation of the fossil content of the Mecca and Logan Quarry shales naturally raises the question as to the relative completeness of the fossil record.

Since a very few leaves and stem pieces of land plants were recognizably preserved we must conclude that very little material of this sort reached the depositional environment directly. Such leaves as might have been blown over the Mecca and Logan Quarry sites landed on the *flotant* and decomposed before they reached the bottom.

The invertebrate picture is rather interesting. Forms with aragonitic as well as phosphatic shells and tests are present in the channel clod, the fresh-water humulite, and the black and gray sheety shales. In the channel clod and the lateral transgression shell breccia the fauna is varied, and *Desmoinesia* occurs in tremendous numbers of individuals. In the humulite it is *Myalina* that has a very great burial density. In the sheety black and gray shales *Dunbarella* is found in countless numbers of individuals, but only in the basal levels of the profiles of both the Mecca and Logan Quarry shales. In both horizons the higher levels contain no *Dunbarella,* and the invertebrate fauna appears impoverished in both number of species and individuals. The above distribution of the invertebrates shows beyond doubt that the burial environment of the higher black shale levels was perfectly satisfactory for the recording of the presence of the shells of these animals, at least as imprints. Even animals lacking hard shells, such as oligochaete worms (pl. 21, C) have left recognizable imprints, although none of the animals' substance was preserved. Since we have made an exhaustive survey of the fossil content of Mecca Quarry (p. 10) it seems highly unlikely that we have overlooked any species occurring in the shale or that the scarcity of invertebrates in the higher shale levels is due to the sampling procedure. We must conclude that only a limited number of species of invertebrates were present in the burial environment and that of these species there were few individuals.

The completeness of the fossil record of the vertebrates is discussed in connection with the question of burial density (p. 189). It would seem probable that they were present in the burial environment of the channel clod, although only meager remains (an occasional scale or piece of cartilage) can be found. The preservation of partial or entire specimens requires very special, highly critical conditions that prevailed only in the sheety black shales at certain locations (residual ponds, see p. 222).

3. *THE CHARACTER OF THE FOSSIL CONTENT*

Those aspects of the fossil content in the Mecca and Logan Quarry shales that are primarily concerned with the fate of the individuals immediately prior to and following death, but before ultimate burial, may be discussed under this general heading. They include such topics as the state of fragmentation and disarticulation of the preserved skeletal elements, the cause of death and the factors that determined the subsequent fate of the carcasses.

a. FRAGMENTATION AND DISARTICULATION

The skeletal structures of the various faunal elements have suffered both fragmentation and disarticulation. Since the two processes are not wholly the result of the same cause they will be discussed separately.

1. Fragmentation

Mecca Quarry Shale at Mecca Quarry

Invertebrates: The vast majority of the individuals of the most common invertebrates in the Mecca Quarry are broken into many pieces. The relatively rare small species, for example, orbiculoids, occur whole. The pectinoid *Dunbarella* is very common in level D, but most of the material consists of shell fragments that are strewn over the fine bedding planes of this level. Whole right and left shells are relatively rare by comparison with the amount of shell debris. Cephalopod phragmocones occur intact or occasionally in several pieces that lie close together (pl. 22, F). The single common arthropod, *Concavicaris,* which consists, in the Mecca Quarry collection, exclusively of the bivalved carapaces (abdomina and appendages have not been identified; pl. 22, A), and which has a characteristic ornamentation, is readily recognizable in very small fragments. Entire carapaces are relatively rare. Plate 22, B and C, shows individuals that were fragmented by predators.

Vertebrates: The degree of fragmentation of skeletal elements varies within wide limits but depends generally on the size and delicacy of the particles. Isolated cartilage elements, except for very small ones, are rarely found intact. Palaeoniscoid scales and bones, on the other hand, are rarely broken. In aggregations of skeletal material, the range of fragmentation covers virtually all possible states from essentially none to extremely fine mincing.

In the channel clod (see p. 58, Stratigraphic Section, West Montezuma), productid brachiopods (*Desmoinesia*) occur in concentrations up to two feet thick. Most of the valves are whole and the delicate shell spines are sometimes seen in interlocking position (pl. 23, A).[1] Other brachiopods, snails, and cone-corals associated with the productids in these banks likewise show little breakage. Some of the cephalopod shells are broken.

The channel clod at other localities (Montgomery Creek, Dee Hollow) contains mostly fragments of the same faunal elements as at West Montezuma.

The transgression shell breccia beneath the Mecca Quarry shale at all localities where it was observed contains a breccia of miscellaneous brachiopod, cephalopod, snail and unidentifiable shell pieces.

Logan Quarry Shale

Invertebrates at Logan Quarry are primarily cephalopods (coiled nautiloids of enormous dimensions, and goniatites), usually represented by whole shells lacking the living chambers. The vertebrates, likewise, show very little fragmentation, compared to those in the Mecca Quarry. However, some breakage of elements is found even in specimens that are by and large intact. Specimens in which much of the skeletal material is fragmented occur much more rarely at Logan than at Mecca Quarry.

In Garrard Quarry, *Myalina* occurs in enormous quantities in Zone 4 but most of the specimens are broken. Sometimes, in Zone 4, finely fragmented *Myalina* shells occur in sharply defined, long and narrow accumulations (pl. 23, B). *Lingula* shells are generally whole, even in such large aggregations as that illustrated (pl. 23, C and D), where the only injury to the specimens resulted from the splitting of the shale. In Zone 8, however, *Lingula* and *Dunbarella* are broken. Fragmented specimens of the shrimp-like percarid crustacean were noted, including a number of separated tails.

In Zones 7 and 8 complete shells of *Dunbarella* are common among much shell debris. In Zones 7 to 9 the cephalopods are unbroken, except, again, for the living chambers. At Big Pond Creek, where *Dunbarella* and *Pteria* are extremely abundant, the shells are predominantly intact. Occasionally the smaller pelecypods are concentrated in parallel tracts on the bedding planes (see pl. 24, A).

Of the vertebrates, a large rhipidistian occurs as isolated bones, scales and teeth, none broken. A pleuracanthid is represented (in the collection) by unbroken teeth only; no cartilage elements were noted. The palaeoniscoids, frequently near-perfect specimens (pl. 40, C), and the acanthodians show very little fragmentation.

At Haworth Creek, in the basal *Myalina* level, the shells are less crowded and less fragmented than at Garrard Quarry. In the *Dunbarella* zone, whole shells of *Dunbarella* and *Pteria* are common among notable amounts of shell debris. The cephalopod phragmocones are generally intact.

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[1] Broken shell material is present in these banks, but much of the breakage is due to the handling of the sediment, which is loosely flaky when dry.

Discussion

The fragmentation of the skeletal elements of both invertebrates and vertebrates may be caused by purely mechanical forces and by predation. Mechanical forces were probably responsible for the rubble contained in the transgression shell breccia and in the channel clod at such localities as Montgomery Creek and Dee Hollow. It is probable that productid banks were growing *in situ* very close to Pit 3 at West Montezuma and that the channels were connected with the open waters of the epicontinental sea to the southwest; thus they must have been subjected to tidal in- and out-wash that kept the sediment disturbed.

In the sheety black levels of both the Mecca and the Logan Quarry shales there is little evidence of water movement (see p. 156), but the parallel, linear distribution of pelecypods on some bedding planes of the *Dunbarella* level at Big Pond Creek (pl. 24, A) might be interpreted as ripple marks of mild waves in a soft, highly organic sediment, though there is no relief on the bedding planes. Such movement as there was did not result in the destruction of the shells.

In the absence of currents strong enough to move particles (or even to orient them; see p. 156), mechanical causes for the breakage of the shells of invertebrates may be ruled out of the question. The hypothesis that they were destroyed by predation is more difficult to prove since most invertebrates show few direct clues of this sort. In the case of the vertebrates, however, there is an overwhelming body of evidence to prove that predation was the principal cause for the fragmentation of skeletal elements (see p. 136). The case for the invertebrates thus rests primarily on analogy and the lack of convincing alternative explanations (see pp. 135, 138).

2. Disarticulation

Disarticulation of vertebrate and invertebrate skeletons is primarily due to bacterial decomposition of the soft parts that join the skeletal elements together in life. Small scavengers may also be involved. Wounds inflicted by predators, especially upon vertebrates, favor rapid bacterial decomposition of soft parts, and thus disarticulation, as will be demonstrated below.

Mecca Quarry Shale

Almost every bedding plane in the Mecca Quarry is littered with predominantly vertebrate debris (see p. 144, horizontal distribution): *Petrodus* scales, *Listracanthus* spines, "placoderm" plates, shark teeth and cartilage elements, palaeoniscoid scales and skull bones. Here and there among this debris there are aggregations of skeletal elements that belong (in the vast majority of cases) to a single individual but rarely constitute the remains of a whole individual. The skeletal elements in finds of this sort are almost invariably disarticulated and often packed within a well-circumscribed area (pl. 40, A). Occasionally, however, the remains are not packed, and while the skeletal elements are in a state of disarticulation it is still possible to discern the principal body regions of the individuals, such as the head region, the main body, and the tail region (pl. 40, B). Complete articulated individuals have not been found, and articulated partial individuals are exceedingly rare in the Mecca Quarry.

Among the invertebrates, *Dunbarella* in level D is almost always disarticulated; no specimens have been found with both right and left valves intact. The hinge ligament must have decomposed entirely, prior to burial. *Concavicaris*, on the other hand, is often preserved with both right and left valves superimposed (pl. 22, A), but there is a complete absence of limbs, abdomina and rostral plates. This is a mystery, since these parts should be as readily preservable as the valves, and even if they were not mineralized they should have left at least impressions. The answer may lie in part in predation by the smaller fishes. The only disarticulation possible in tetrabranchiate cephalopods is that between shell and aptychus and between valves of the aptychi. A coiled cephalopod,[1] essentially intact, was found a short distance from what looks like an aptychus of about the right size to go with the shell. The presumed aptychus is horizontally divided by a thin sheet of matrix, perhaps indicating that both valves are present, preserved in perfect congruence. If this is indeed the correct interpretation we must conclude that the aptychus came loose from the shell, but that the valves remained attached to each other until burial. A few associations of conodont jaw elements were found among the numerous dissociated conodonts.

In the channel clod at West Montezuma virtually all *Desmoinesia* shells have dorsal and ventral valves in place. Disarticulated specimens are exceptional. Other brachiopods are more commonly disarticulated.

Logan Quarry Shale

In sharp contrast to the Mecca Quarry there is virtually no litter on the bedding planes of the sheety shale at Logan Quarry, except for a single horizon in the middle of level J, where there is a conspicuous amount of disarticulated acanthodian and palaeoniscoid material. Disarticulated vertebrate remains of the type described above for the Mecca Quarry also occur at Logan Quarry, but most specimens are intact, except in the vicinity of wounds (pl. 33) inflicted by predators (see below).

The pelecypods at Big Pond Creek and Haworth Creek are for the most part disarticulated individuals but many whole individuals were noted.

Garrard Quarry

In the Garrard Quarry the *Myalina* shells are usually disarticulated, but specimens with right and left valves in position of attachment (though opened up) are fairly common. In a large concentration of *Lingula* in Zone 6 (pl. 23, C, D) most individuals seem to have both valves in place. In Zones 7 and 8 *Lingula* is usually disarticulated. *Dunbarella* is almost always disarticulated.

The shrimp-like percarid crustacean occurs in whole specimens as well as in parts that may have been bitten off.

Of the vertebrates, the large animals (pleuracanthid and a rhipidistian) are totally and the acanthodians partly disarticulated. The palaeoniscoids are either perfectly intact, including the minute fin rays to the margins of the fins, or very slightly disarticulated (pl. 40, C).

Discussion

The palaeoecological significance of disarticulation lies in the great speed with which aerobic bacteria are capable of dissolving the soft parts of animals under water, given favorable temperature conditions (see p. 162), and in the evidence it affords concerning the feeding behavior of the predators and the performance of their digestive systems. Articulated aquatic fossil vertebrates and invertebrates indicate either virtually immediate burial in sediment, or a highly poisoned bottom (for example, by quantities of H_2S) where aerobic decomposition is quickly superseded by the much slower anaerobic rotting process. At the site of the Mecca Quarry, burial must have been rapid. Specimens that were but slightly injured are preserved in nearly perfect articulation (for example, "placoderm" PF 2821, acanthodian PF 2875). In view of the evidence presented (see p. 161, rates of deposition,

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[1] We cannot at present identify it as a nautiloid or a goniatite; the X-ray picture gives no information.

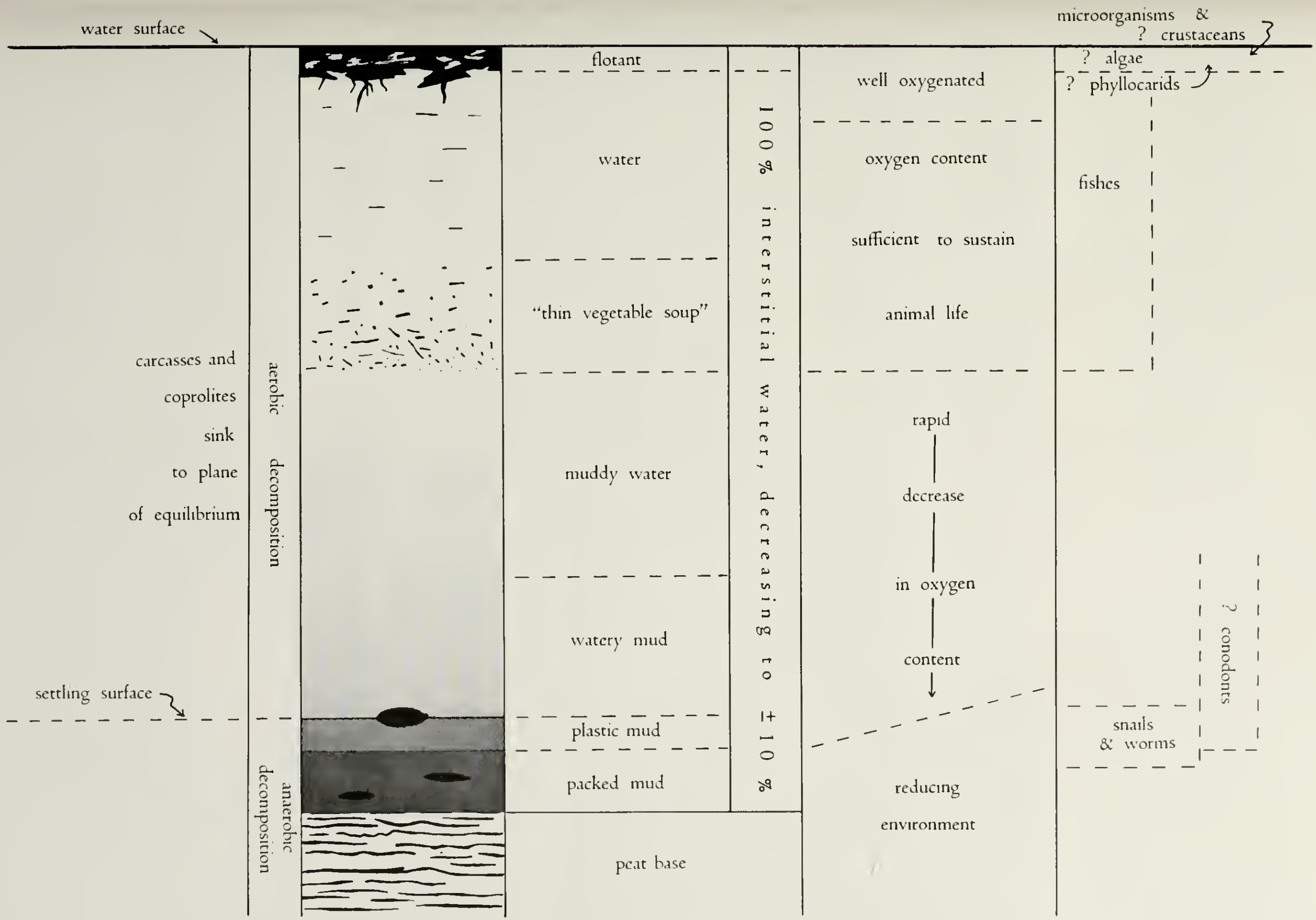
water surface
microorganisms &
? crustaceans
? algae
? phyllocarids
flotant
water
"thin vegetable soup"
muddy water
watery mud
plastic mud
packed mud
peat base
100% interstitial water, decreasing to ± 10 %
well oxygenated
oxygen content
sufficient to sustain
animal life
rapid
decrease
in oxygen
content
reducing
environment
fishes
? conodonts
snails
& worms
carcasses and
coprolites
sink
to plane
of equilibrium
aerobic decomposition
anaerobic decomposition
settling surface

FIG. 27. Our interpretation of habitat and depositional environment of Mecca and Logan Quarry shales in residual ponds, based mainly on faunal and lithologic evidence, and including some observations on similar modern environments.

and p. 176, compaction) we must conclude that the specimens at Mecca Quarry sank rapidly through a column of increasingly dense mud (fig. 27) to a fairly firm settling plane. There, aerobic decay was soon terminated in favor of anaerobic rotting in a micro-environment that lacked oxygen but was not completely stagnant and therefore not very highly charged with hydrogen sulfide and other poisonous compounds. This evidence alone would indicate that the great amount of disarticulated skeletal material at the Mecca Quarry was not produced by bacterial decomposition but by the effects of predation; direct evidence for this conclusion will be set forth below.

Essentially similar conditions must have prevailed at Logan Quarry. The striking differences in the preservation of the fossil content at the two sites may be explained by more rapid deposition of mud at Logan Quarry, differences in the faunal composition, e.g. the almost total absence of *Petrodus* and scarcity of *Listracanthus*, and probably differences in the mode of predation.

At the Garrard Quarry, Zones 5, 6, and 7 are very highly pyritic (see p. 126). Palaeoniscoid fish carcasses present especially in Zones 5 and 6 show no signs whatever of disarticulation (pl. 40, C). There seems little doubt that the location became stagnant and that the bottom conditions were severely poisonous; the rate of deposition may have been much slower in this part of the section than during deposition of the transgressive beds above. Decomposition appears to have been entirely anaerobic.

In both the Mecca Quarry shale and the Logan Quarry shale there frequently occur disarticulated vertebrate specimens of characteristic appearance. These are sharply circumscribed masses of tightly packed skeletal elements up to an inch in thickness. While the skeletal content of most of the specimens of this type belongs to one species and usually to but one individual, cases are known where the remains of two or even three different animals, sometimes of different species, are mixed together. The interpretation of these specimens as regurgitated residual stomach contents of predators is discussed in greater detail below (p. 139). The disarticulation in these specimens is due to the dissolution of the soft parts of the prey by gastric juices, not bacterial degradation. As might be expected, masses of regurgitated stomach content are not all alike; their particular differentiation depends on the food animal, the length of the period of retention in the stomach, the size and probably the species of predator, the vehemence with which the content was regurgitated, and the relative fluidity and compactability of the content (for the biological and behavioristic significance of these differences see p. 140).

It would appear rather probable that much of the isolated debris at the Mecca Quarry originated from fluid and uncompactable ejects.

b. THE CAUSES OF DEATH

1. Introduction

In an environment with the physical characteristics determined for the Mecca and Logan Quarry shales there are potentially numerous causes of death of individuals of the enclosed fauna. The shallow depth of water and the large quantity of decomposing vegetable matter would suggest low levels of oxygen present in the water, resulting at least occasionally in death due to asphyxiation. Under such circumstances, furthermore, poisonous compounds (ammonia and hydrogen sulfide) develop, and one would expect some death due to poisoning. It is possible that mortality was due to relatively high water temperatures or to drastic changes in the salinity in shallow ponds, which in similar situations at the present may range from fresh to hypersaline (Gunter, 1952). In view of the vast concentration of vertebrates in the black shale at Mecca Quarry, one is tempted to think of mass mortality due to one, or a combination of several, of the factors mentioned. As will be shown below, such a conclusion is not warranted, nor the supposition that any of the factors mentioned above played a significant role in the cause of death of the vertebrates at Mecca and Logan Quarries. At Garrard Quarry, on the other hand, the situation was different. While there is direct evidence concerning the cause of death of the Mecca and Logan Quarry vertebrates (see below) we are limited to indirect evidence at Garrard Quarry.

2. GARRARD QUARRY

The vertebrate occurrence at Garrard Quarry is not very dense; in no sense of the word was it a mass burial ground. Specimens were recorded in Zones 4 to 8, but they are most numerous in Zones 5 and 6. The large forms, a rhipidistian and a pleuracanth shark, occur in Zones 4 and 5, disarticulated but not fragmented. The cause of their death cannot be determined, but it was probably not predation. The palaeoniscoids in Zone 4 are represented only as isolated scales and skull bones; not a single whole or partial specimen was observed. Palaeoniscoids no doubt were preyed upon, since their scales are occasionally seen in coprolites and in sharply defined packed masses of bones and scales (see p. 140, gastric residues). In Zones 5 and 6, however, they occur also as whole fishes, usually in a near-perfect state of articulation (pl. 40, C).

Zones 5 and 6 contain such quantities of sulfides (see p. 126) that the bedding planes are olive-green in color. This would suggest that the bottom conditions were highly poisonous; since there is no evidence of mass mortality, and since the bedding of the olive humulite of Zone 6 is extremely fine and even (there could have been no disturbance of the bottom whatsoever), we must assume that the surface water was free of noxious chemicals and sufficiently well aerated to permit normal activities of the organisms. It is thus probable that the palaeoniscoid fishes occasionally and accidentally darted into the bottom water (perhaps to seek shelter beneath loose, decaying vegetation) and were poisoned. A similar cause of death may apply to the whole specimens of the shrimp-like percarid crustacean.

The cause of death of *Myalina* at Garrard Quarry was primarily predation. In Zone 4 most shells are fractured and there are numerous concentrations of finely minced shell material (pl. 23, B); in Zones 5 and 6 these concentrations are well-defined, fairly thick masses of somewhat coarser shell debris (pl. 44, D). It appears virtually certain that the predators crushed large numbers of individuals by mastication and then disgorged the indigestible shell material. The concentrations in Zones 5 and 6 look like regurgitated stomach residues.

Dunbarella in Zones 7 and 8 never occurs in aggregations of the type described for *Myalina.* It is very probable, however, that the fractured individuals were eaten, perhaps one at a time (which is not an unreasonable supposition in view of the notable mobility of these pelecypods), and that the crushed shells were immediately discarded. We have no record of possible predators on molluscs at Garrard Quarry.

The individuals with uncrushed valves, both in place, obviously were not eaten. Since pectinoids are animals that rest on the bottom—between spurts of active swimming—we must assume that they entered the Garrard situation from their normal habitat along the fringes of the epicontinental sea over suitable bottom conditions and over a period of time. In the area of the Garrard Quarry, however, the bottom was severely toxic (Zone 6 to base of Zone 8). It seems very likely that these animals died of hydrogen sulfide poisoning. This conclusion is re-enforced by the fact that upward from the base of Zone 8 the specimen density decreases as the sulfide content of the shale decreases.

3. Logan Quarry

The determination of cause of death of the vertebrates at Logan Quarry presents little difficulty; at no other locality of any age has evidence of predation as the principal cause of death been more dramatically preserved than at this site. Nearly every specimen recovered shows signs of mutilation ranging from simple bite marks to amputation of parts, to bisection of larger prey, to badly chewed but evidently not swallowed specimens or parts. In addition there is a wealth of evidence concerning prey actually eaten.

The identification of the cause of death in the terms stated is based on the following evidence:

Vertebrates

(a) Whole Skeletons: There are a very few shark skeletons that do not show clear-cut signs of mutilation, but in all of these cases the negative evidence is suspect because the specimens have been incompletely collected in the quarry. In the individual (PF 2428) illustrated (pl. 30), for example, it seems unlikely that the posterior half of the specimen would have been missed; it is much more probable that only the anterior half was present and that the missing portion was bitten off.

The large shark (PF 2201, pls. 24, B, and 25) from level J, Logan Quarry, shows no obvious effects of predation (unless the fracture in the jaw element indicates such an injury). The overall aspect of preservation of this specimen is of great interest, however, since it indicates environmental conditions that might have been responsible for the death of the animal. The burial position of the skeleton is dorsal side down in the formation. The shagreen of the back is undisturbed, but outlining the body there are conspicuous ridges of scales. We conclude that soon after death the animal bloated and turned belly side up. At that time it must have floated long enough to have turned over. Then the abdominal skin burst and the frayed edges rolled up. Since the rest of the skeleton is preserved in articulation we must assume that it did not float freely in the water while decomposing. Furthermore, some agency must have kept the skeleton (especially the skin denticles) from being displaced even slightly. The covering of the skeleton was (before preparation) the "black band" of level J. This consists almost wholly of degraded opaque plant debris. The evidence suggests strongly that this represents the *flotant* itself, draped over the carcass as it lay on the bottom in extremely shallow water. It is further probable that the site actually dried up and that the *flotant* held the skeleton perfectly in place beneath it, when the water level rose again. It is commonly observed that algal scum in a puddle that has dried out adheres firmly to the bottom even after the pool has filled up again. If our interpretation is correct we must conclude that the animal was trapped in a very shallow pond and may thus have become poisoned or asphyxiated.

(b) Specimens Showing Evidence of Bite Wounds: In this category belong specimens that are essentially whole individuals, near-perfectly articulated, except for local, usually linear, areas of disturbance. This is most often seen in palaeoniscoid fishes (pl. 27, A). In cases of this sort the bite did not sever the body of the prey, but merely crushed it along the impact line of the predator's tooth row. Much more common, however, are specimens in which parts of the body have been cut off. The severed parts are still with the carcass, usually in proper relation to it, which would indicate that severance was incomplete and that the parts remained attached to one another by connective tissue (pl. 27, B).

The injury to the tail fin suffered by the fish illustrated in plate 26, B, no doubt incapacitated the animal. It seems probable that the bite wound as such did not directly cause its death; it probably struggled, unable to support its heavy body with its small fins, and sank into the mud, where it became asphyxiated or poisoned.

Evidence of bite injuries is also frequently seen in shark specimens. Specimens buried in dorso-ventral position are often injured (and the cartilage elements broken and disarranged) on one side of the sagittal plane, though the other side is undisturbed (pl. 32). Such an injury undoubtedly caused the dislocation of the vertebral column of the shark PF 2202 (see fig. 38).

(c) EVIDENCE OF AMPUTATION: Many specimens from the Logan Quarry consist of near-perfectly articulated partial individuals. Palaeoniscoids lacking skulls or tails or both occur with notable frequency (pls. 26, A, 34, B). The common small acanthodian had the body habitus of an eel; the specimens, for this reason, most often occur as pieces of "sausage" cut at one or both ends (pls. 28 and 33). Evidence of amputation is even more striking in the sharks. Most of these specimens consist of only the skulls with or without the shoulder region, or of the tail area alone (pls. 30 and 34, A). Furthermore, there is a moderate number of shark specimens in which the vertebral column is not entirely missing between skull and tail. This may be looked upon as strong evidence for the belief that the predators (almost certainly sharks themselves) attacked other sharks from beneath, perhaps in order to get at the livers (pl. 31).[1] There is, furthermore, evidence that the predators were selective in the consumption of the prey. It is the muscular trunk region that is most often missing in the carcasses (pl. 30); in the detached tail specimens it is most often the dorsal lobe of the fin (covered on both sides with muscles in life) that is either mutilated or missing, while the ventral lobe, consisting only of cartilaginous fin-rays and skin, is either undisturbed or merely bitten and relatively little disturbed (pl. 35).

(d) EVIDENCE OF MOUTHING: A large number of specimens display marks of moderate to severe mutilation, but there is no evidence that they were swallowed by the predator (pl. 26, C). Such specimens show broken skeletal elements and some amount of disarrangement of the skeleton, but there is rarely a complete mixture of parts from different areas of the skeleton (pl. 37); the major regions are still recognizable *in situ*. These specimens are not accompanied by tufts of brownish matter resembling (in the fossil condition) fecal material.

Comparison of specimens of this category with those that show bite marks and more severe injuries suggests strongly that the predators killed and chewed the prey without intent to feed.

(e) EVIDENCE OF FEEDING: The material recovered from the Logan Quarry includes many specimens that serve as unmistakable evidence of feeding, primarily by the predators. Such specimens may be classified as stomach ejects, gastric residues, and coprolites. These will be described below.

Invertebrates

The only invertebrates of some abundance in the Logan Quarry are the cephalopods. Most of the specimens are nearly intact, indicating, in view of the situation at Mecca Quarry (see below), either a different mode of predation or a cause of death other than by predation. Most of the giant nautiloids are preserved in level F, which contains a great amount of stream-borne clastics. It is possible that the introduction of large quantities of fresh water may have lowered the salinity below the tolerance level of the nautiloids.

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[1] This conflicts with observations on the behavior of modern sharks, which attack their prey from above (see p. 196).

4. Mecca Quarry

The causes of death of the vertebrates at Mecca Quarry were virtually the same as at Logan Quarry. Injuries inflicted by predators are less obvious in the material from the Mecca Quarry, probably because such injuries have been obscured by bacterial decomposition, which appears to have been more pronounced (except in level C) at Mecca Quarry (see p. 172, slower rate of deposition). Partial specimens, however, are common and indicate predator activity.

The cause of death of the pelecypod *Dunbarella* in level D is not particularly obvious. Many specimens are broken and may have been eaten, but there are no shell heaps that resemble gastric residues. The population density was high throughout level D, which rules out the possibility of mass mortality of any sort. The abrupt lack of *Dunbarella* above level D may be due to the lowered salinity in the succeeding levels (p. 221). There is no convincing evidence for or against the assumption that there may have been a connection between the Mecca area and an open lagoon through which *Dunbarella* might have come to the Mecca Quarry site during level D deposition. The possibility remains open.

The crustacean, *Concavicaris*, was preyed upon by sharks. Proof of this lies in a specimen (PF 2469) from Logan Quarry, a shark which has a readily recognizable phyllocarid among its gastric or intestinal content. A great many of the individuals at Mecca Quarry appear to have been chewed to pieces (pl. 22, B); hence the large number of fragments of carapaces. Specimens with both valves more or less in place might possibly represent empty hulks shed during the molting periods, but this cannot be determined at this time.

The majority of the cephalopods at Mecca Quarry consist of broken phragmocones. Since shell pieces of similar type of preservation occur in accumulations of gastric residue and even in fecal masses, it seems reasonable to conclude that these molluscs were preyed upon and that their shells were broken and scattered in the process. The few individuals whose shells appear to be essentially uninjured may have died of injuries to their soft parts or may have been poisoned.

Conodonts are scattered throughout the Mecca Quarry shale. Jaws are sometimes concentrated around gastric residues and stomach ejects; they are but rarely part of such specimens. From this it would appear certain that the organisms bearing these jaws were somehow associated with the specimens with which they are found. The type of association,[1] however, is by no means evident. In view of the uncertainties involved it seems useless to speculate upon the possible causes of death of these organisms.

c. THE FATE OF THE CARCASSES

1. Introduction

Under exceptionally favorable circumstances evidence may be preserved that permits insight into what happened to an animal from the moment of its death to the time of its burial in the sediment. The necessary conditions include lack of scavenger action, absence of bottom fauna and infauna that disturb the sediment of the burial ground, and the rather gentle subsequent bacterial decomposition of the organic substance under cover of rapidly accumulating sediment. These conditions prevailed at the sites of both the Mecca Quarry and the Logan Quarry, as well as at a number of other localities in the area of the present study.

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[1] It is possible that the conodonts fed upon the gastric residues; or they may have been parasites of the prey (for example, after the fashion of monogenetic trematodes that attach themselves to the gills of fishes); or they may have been eaten by the predators along with other prey.

Those individuals in the fauna that died of causes other than predation and those that were mutilated but not eaten by the predators evidently settled into the mud without being further disturbed. Their skeletons either are unbroken and articulated or show the marks of mutilation. It was thus surprising to find, along with specimens of this sort, others that are totally or partially disarticulated. Careful comparison of hundreds of specimens revealed beyond any doubt that the disarticulated specimens represent individuals eaten by predators. Disarticulation is thus primarily the result of partial to nearly complete digestion, rather than of bacterial decomposition of the soft parts.

Evidence in support of this conclusion is set forth below. But our analysis has also revealed the interesting fact that the prey produces fossils of distinctive characteristics, which in turn permit conclusions as to the feeding behavior of the predators—primarily sharks—and the functioning of their gastro-intestinal systems.

2. Interpretation of Disarticulated Specimens

The collection of fossil animals from the Mecca and Logan Quarry shales may be divided into two groups: those that are either wholly, or at least in part articulated, and those that are entirely disarticulated. The latter group is of interest in the present connection. In all cases, disarticulated specimens (in contrast to scattered debris) consist of the skeletal remains, usually of only part of an individual, that are strewn over a small area of shale, rarely exceeding one square foot in size. Within this area the skeletal components (scales, teeth, bones or pieces of cartilage) are more or less densely distributed, often tightly packed together. Sometimes the margins of the specimens are fairly sharply defined, in other cases they are ill defined, the skeletal accumulation spreading in one or several directions from an area of greatest density (pls. 41, A, and 44). Another peculiarity of these specimens is the presence, usually all over these remains, of small tufts of a brownish material, similar in appearance to the groundmass in coprolites. In most cases, such accumulations consist of the skeletal remains of but a single individual, for example a portion of a palaeoniscoid fish or acanthodian or shark. But a large number of specimens of precisely this kind occur in which there is a mixture of skeletal remains of two individuals of the same group (for example, the head regions of two palaeoniscoid fishes; pl. 45, C) or parts of individuals of different groups, for example, the head region of a palaeoniscoid fish intermingled with the calcified cartilage debris of a shark tail fin. The intermingling of the skeletal material of such mixed aggregations is often incomplete and the components may show different degrees of disarticulation (pl. 42, B). Virtually all possible combinations among the more common elements of the fauna have been observed and there are a few specimens containing remains of more than two different types of animals. The following list gives the combinations and the number of specimens in each category among the gastric residues from the Mecca Quarry:

Combination	No. of observations
Palaeoniscoid + "placoderm"	21
Palaeoniscoid + shark	20
Palaeoniscoid + acanthodian	8
Palaeoniscoid + problematicum	3
Palaeoniscoid + *Listracanthus*	1
Acanthodian + "placoderm"	3
Acanthodian + shark	1
Shark + "placoderm"	1
Shark + cephalopod	1
"Placoderm" + *Listracanthus*	1
Palaeoniscoid + acanthodian + "placoderm"	1
Palaeoniscoid + "placoderm" + *Listracanthus*	1
Palaeoniscoid + acanthodian + incognitum	1

It seems highly improbable that skeletal aggregations of the type described could have come about by chance alone. The occurrence of mixed aggregations and the presence of material resembling coprolitic groundmass in these specimens strongly suggest that the disarticulated material represents ingested and subsequently regurgitated prey. This interpretation is not as far-fetched as it may seem in view of observations on the feeding behavior of modern sharks, which are known to regurgitate food and difficult-to-digest food residues that accumulate in the stomach (Strassen, 1914; Müller, 1957).

A more detailed analysis of the specimens interpreted as regurgitated prey reveals further aspects of the feeding behavior of the predators. The specimens appear to fall into two groups: ejected prey and gastric residues.

(a) *Ejected prey:* Some of the specimens—not a very large number—display the following characteristic features: The remains comprise whole or partial skeletons in disarticulated and disoriented condition, but the principal regions of the body (head region, thoracic region, tail portion) are usually still in proper spatial relationship to one another (pl. 42, A). Here and there some of the skeletal elements may still be in articulation, for example, small patches of scales or parts of the skull (pl. 36). The specimen is usually strewn with small tufts of a brownish material resembling the groundmass of coprolites. The surfaces of the skeletal elements are usually bright; there is little evidence of etching.

Specimens of this sort differ from those that have been severely mouthed (see above, p. 137) but evidently not swallowed, by the presence of the brown material and the greater degree of disarticulation. Needless to say, there is an occasional specimen that defies classification into one or the other of these categories. Much less sharply drawn is the distinction between these specimens and the gastric residues.

(b) *Gastric residues:* A great many specimens from both the Mecca Quarry and the Logan Quarry consist of totally intermingled skeletal material, either tightly packed into pellet-shaped, thick masses (pl. 44, A–C) or more or less loosely strewn over small areas of shale (pls. 41, A; 45, C). Invariably the skeletal debris is accompanied by varying quantities of brownish material resembling fecal ground substance. While some of the loosely strewn gastric residues resemble ejected prey, many of the pellet-shaped masses cannot be definitely distinguished from coprolites.

The fact that the categories here described are connected by specimens of intermediate characteristics strengthens the present interpretation of the nature of these fossils.

(i) Loosely strewn gastric residues: Depending on the nature of the food (shark, "placoderm," palaeoniscoid or acanthodian), the size of the prey, and the size of the predator, these residues vary notably in appearance. In nearly all cases, however, the skeletal components are totally intermingled and splattered over a limited shale surface. The arrangement of the debris on the bedding plane, however, usually shows a characteristic pattern: there is a small area in which the debris is densely aggregated, often even piled up; peripherally the density falls off sharply, and the spaces between debris particles increase in size with the distance from the center of greatest density. The spread of the particles may be symmetrical around the density center, or it may fan off to one side only.

(ii) Pellet-shaped gastric residues: Sharply circumscribed, thick masses of skeletal debris embedded to a varying degree in a brown groundmass are very characteristic fossils in the Mecca and Logan Quarry shales. If the skeletal content belongs to a palaeoniscoid fish, it usually consists of great masses of scales, tightly packed and stacked like cards; long bones such as mandibles often protrude from the mass on one side (pl. 44, B). If the content is acanthodian the bulk of the mass consists of countless tiny cubic scales and usually fin spines that protrude from the mass on one or two sides (pl. 45, A and B). Pellets containing shark or "placoderm" remains consist of calcified cartilage prisms (either organized as recognizable cartilage elements, or partly dissociated) and—depending on what portion of the prey was ingested—other hard parts such as placoid scales, teeth, spines and, in the case of "placoderms," bone plates and tooth whorls (pl. 43, A–C).

Gastric residues intermediate in appearance between pellets and splatters are very common, as might be expected.

Internally, gastric residue pellets (pl. 46, A–D) show relative uniformity of the mass except where the remains of two different animals have not become completely intermingled (pl. 46, C). This is a notable difference between the stomach pellets and the coprolites (see below). Gastric residues consisting of the remains of two different animals sometimes show differences in the degree of digestion; for example, the scales of one animal may be shiny, those of the other dull, presumably etched, which would indicate the relative length of time during which the food components remained in the stomach. Hence, it is possible to determine the sequence in which the food was ingested.

(c) *Fecal masses (coprolites)*: Fecal masses (coprolites) occur in a variety of shapes, sizes, and compositions. In all cases they consist of a groundmass of light to dark brown to near-black (bituminized[1] coprolites) material that shows no structure in thin section. Embedded in this material there may be skeletal elements such as teeth, scales, small pieces of spines, bits of bone, sometimes even remains of calcified cartilage. In some coprolites there are no such inclusions, but when present they are always severely etched and show poor structural detail in thin section, although it is still possible to identify them in such general terms as "acanthodian scales," "shark teeth," etc. In volume, the fecal groundmass greatly exceeds the inclusions. In some cases, however, it is difficult to differentiate between a gastric residue and a fecal mass because the brown ground substance is present in both. In many cases the fecal groundmass contains a large quantity of very finely distributed sulfides and sulfates and there is a peripheral layer where these substances are concentrated (pl. 50, A).

The typical fecal masses occur in three readily distinguishable forms: (i) dense, thick, irregularly shaped masses, often large (specimen PF 2652, for example, measures 9 cm. in diameter by 5 cm. in thickness); (ii) tufts of fecal material of different sizes strewn over a limited area (coprolite trains or splatters); (iii) spiral coprolites almost always three dimensionally preserved with no appreciable flattening.

(i) Irregular compact form: Sections through fecal masses of this type reveal that the fecal groundmass is not homogeneous. It consists of fecal components of different color (lighter and darker shades of brown) and density that are often very sharply delimited laterally (pl. 47, A and B). Skeletal inclusions may be found in one bolus but not in the others. These fecal components, furthermore, may be sharply delimited on one side but partially mixed with the surrounding material on the other (pl. 48). The ground substance is often transected by minute cracks (filled with calcite) that run in different directions in the different fecal components of a single coprolite (pl. 47, A). These appear to be shrinkage cracks, but their course seems to have been determined by the alignment of the fecal particles in each component mass. Larger cracks appear to have served as degassing channels during the anaerobic decomposition process, as is witnessed by the sulfide accumulations near the exits of such cracks in the adjacent shale (pl. 47, B).

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[1] The black substance may be apatite (see p. 102).

These internal details indicate that a fecal mass of this sort accumulated over a period of time in the rectal area of the intestine, receiving additions to its bulk at intervals, and that these were incorporated into the main mass by the peristaltic movements of the intestine. In the rectum these movements resulted in the kneading of the fecal accumulation, but the mixing of the later additions with the earlier ones was prevented by the differences in the consistency (relative dehydration) of the various fecal components. Furthermore, the rectal kneading process appears to have had an effect upon the alignment of particles in the more plastic fecal boli, which resulted, in the later shrinkage of the material, in the characteristic cracking pattern of the various components of the coprolitic mass.

(ii) Coprolite trains or splatters: Fecal masses of this sort usually consist of a great number of irregularly shaped tufts of fecal groundmass of varying size, strewn over a small area of shale. As a rule they contain no skeletal inclusions, but in one case, PF 2653, pebbles and crinoid stem pieces are embedded in the fecal mass. Since pebbles are extremely rare in the Logan Quarry shale and crinoids[1] are entirely absent, we must conclude that the predator had arrived at the Logan site from the epicontinental sea to the west but a short time prior to defecation of the specimen in question. In vertical position it lies in the lower half of level J (see p. 109, Microscopic Composition of Shale), which contains a fair amount of clastics and which precedes the black band level at which we have evidence of a short period of virtual drying of the Logan site. The significance of this specimen lies in the fact that it indicates beyond doubt communication between the Logan site and the sea at the time of deposition of the lower half of level J.

(iii) Spiral coprolites:[2] Spiral fecal masses are fairly common in the Logan Quarry shale. They are dense pellet-shaped objects with good internal spiral structure and few inclusions of skeletal debris. They are preserved in the round (pl. 47, C; figs. 28, 29). In a mutilated shark specimen (PF 2207) irregularly formed intestinal content is followed in the pelvic area by a spiral fecal mass.

Since all coprolites so far described in this account must be assigned to sharks (their size would preclude assignment to other members of the fauna), and since we may confidently assume that all sharks possessed spiral intestines, the question arises why some fecal masses retain the shape of the lumen of the spiral intestine and others do not.

Examination of sections through spiral coprolites reveals that their internal structure is not perfectly spiral. Figure 28, representing an ovoid fecal mass in cross section (the illustrated faces are 5 mm. apart), clearly shows that the spiral is incomplete on one cut face of the coprolite and on the other side some of the fecal scroll is incomplete. The nature of the spiral coprolites is still poorly understood. In the literature there are various suggestions as to their origin. Some authors have maintained that spiral coprolites represent the hardened content of the spiral intestine in place, and others have suggested that the fecal mass has been extruded in coiled condition from the spiral intestine into the rectum. The latter view is impossible, as any rubber cast (fig. 30) of the lumen of the spiral intestine of a modern shark will prove.

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[1] Crinoids would seem to be an extremely poor source of food. It is not possible, however, to determine whether a living crinoid was ingested, or whether the shark merely picked up crinoid stem-pieces and pebbles from the bottom.

[2] Two principal types of spiral intestines are known among modern sharks (Parker, 1880). It has recently been suggested that one of these is a relatively modern development. There is evidence of the existence of both types in the Mecca and Logan Quarry shales to judge from the form of spiral coprolites. Since this is a matter primarily of zoological interest, it will be dealt with in greater detail in the future description of the fauna.

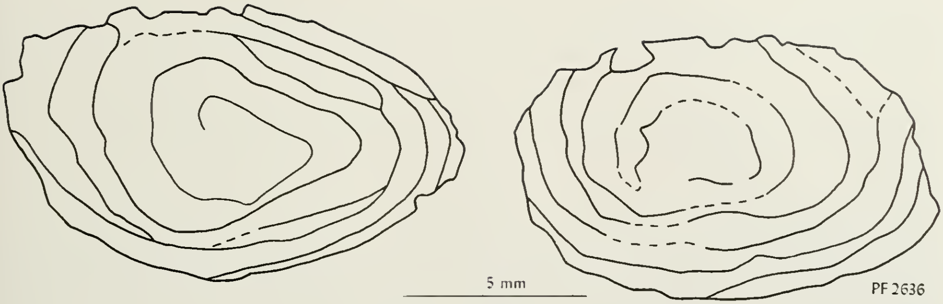


FIG. 28. Cross sections, 5 mm. apart, of a spiral coprolite, showing imperfect spiral coiling. Level J, Logan Quarry.

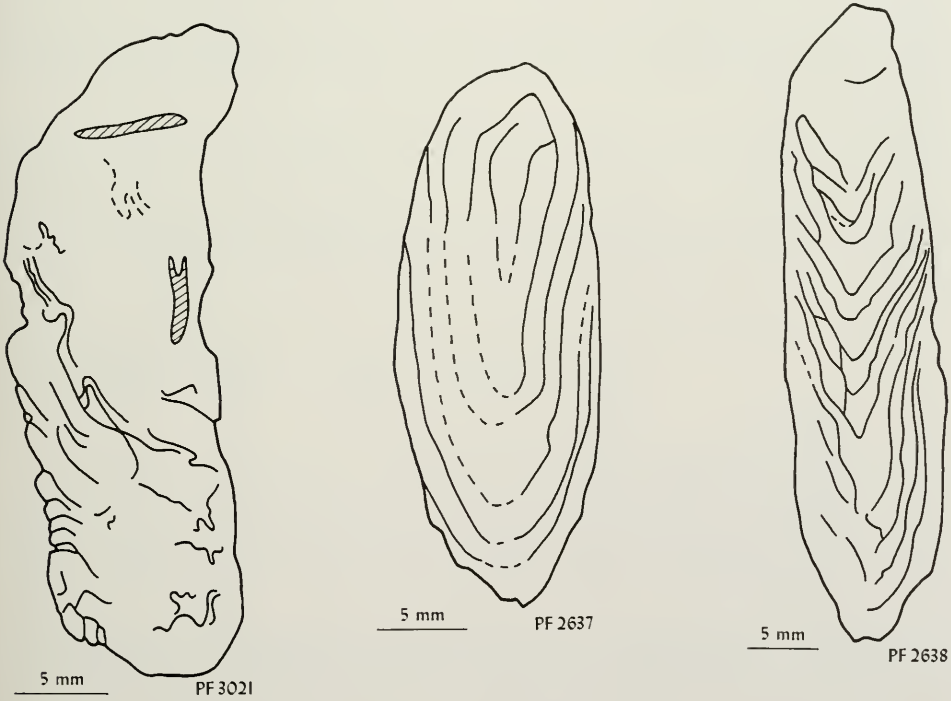


FIG. 29. Spiral coprolites in longitudinal section, indicating presence of sharks with different types of spiral intestines. Left: A coprolite in which the fecal material was presumably too soft to regain coiled structure upon extrusion into rectum from spiral valve; Mecca Quarry shale, Mecca Quarry, levels A4.1–A4.3. Center and right: Coprolites composed of fecal material with spiral structure; Logan Quarry shale, Logan Quarry, level J (center) and uncertain level (right).

The material from the Mecca and Logan Quarries may answer this question. Some coprolites show fairly but not perfectly regular spiral structure internally; in others the spiral arrangement is incomplete, and in some it is very irregular and barely recognizable (fig. 29); furthermore, there are many fecal masses without spiral structure, although we may (to judge from the size) confidently assume that they were shed by sharks. In addition to these, there are fecal masses that formed splatters upon defecation and were obviously poorly consolidated. These observations tend to suggest that the development of a spiral fecal mass is related to the consistency of the fecal matter in the lower portion of the spiral intestine.

A rubber cast of the lumen of the spiral intestine of a modern shark (fig. 30) shows that the fecal mass has the shape of a spiral ribbon. Upon extrusion into the rectum, given proper plasticity, it would probably roll itself into a more or less perfect coil. Deviation in either direction from the plasticity optimum would probably result in imperfect coiling or in lack of spiral structure.

If these deductions are valid we must conclude that the internal structure of a coprolite reflects a temporary condition in the digestive process, primarily related to the absorption of water in the lower intestine. It might also reflect abnormal physiological conditions, brought about by environmental factors. Because of total lack of evidence of this sort in modern situations we are unable to evaluate the material from Mecca and Logan Quarries. We do not know, for example, whether the feces of modern sharks, living under natural and favorable conditions, are by and large uniform in their consistency or whether there is a great deal of variation in this respect depending on such factors as the nature of the food and the individual age of the animal. If it could be established that the feces of modern sharks, under favorable conditions, are generally of medium consistency (say spiral in structure), we would have to conclude that the living conditions for the sharks at the Mecca Quarry site were definitely abnormal, as may be seen in the following tabulation:

MECCA QUARRY COPROLITES[1]

	Splattered	Thin and soft	Spiral	Thick and dense	Total no. of observations
Fecal masses	19	54	6	42	121
Misc. Cops.	1	10		1	12
Mixed Cops.		3		1	4
S-cops.	1	16	1	3	21
A-cops.	2	7		5	14
Pl-cops.	1	3	1	1	6
P-cops.		8	2	5	15
No. of observations	24	101	10	58	193
% of total	12.4	52.3	5.1	30.0	

[1] The prefix of "cop" indicates the nature of the coprolite content: S, shark; A, acanthodian; Pl, "placoderm"; P, palaeoniscoid.

4. *HORIZONTAL AND VERTICAL DISTRIBUTION OF FOSSIL CONENT*

a. HORIZONTAL DISTRIBUTION OF THE FOSSIL CONTENT AT MECCA QUARRY

There have been very few attempts, to date, to chart the fossil content of a formation in its horizontal distribution. Such work as has been published (e.g., Hauff, 1921; Hintze, 1934; Weigelt, 1931) includes only part of the fossil content (e.g., choice specimens) and/or projects the fossil content of a fairly thick portion of the profile into one plane. Such charts thus do not give us any idea of what was deposited at any given time in the area studied. Charts of this sort have paleoecological meaning only if the animal remains were being deposited very nearly at the same time and were thus subjected to the same factors of temperature, current, salinity, etc., within the observed area.

For the Mecca Quarry, horizontal distribution charts of the total fossil content (fig. 4) were made for every quarter-inch of shale (except for level C) and for all faunal elements, coprolites and driftwood separately (see fig. 31, p. 10, methods). A quarter-inch of fairly dark shale required about 40 days for its deposition (see p. 175, rates of deposition); our horizontal distribution charts, like those of earlier workers, thus do not indicate what happened at any given instant in time; instead they record the accumulation of material during a relatively short span of time—a time interval almost infinitesimally small if viewed in the light of its geologic age, but a measure of time far too coarse to record the sequence of events that occur, say, in a shallow pond about to dry up.

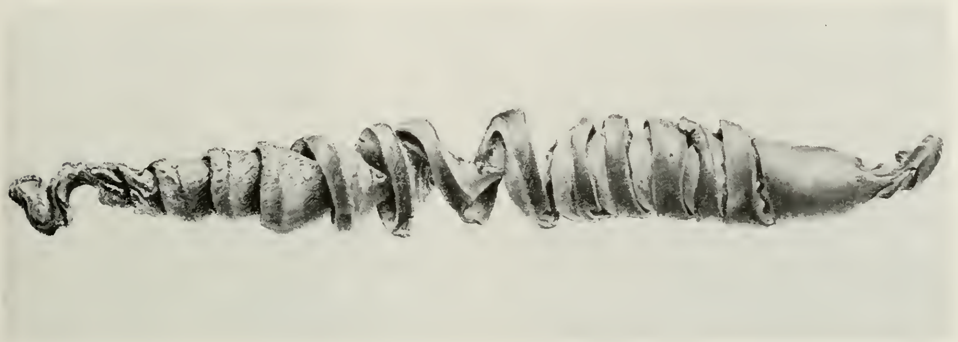


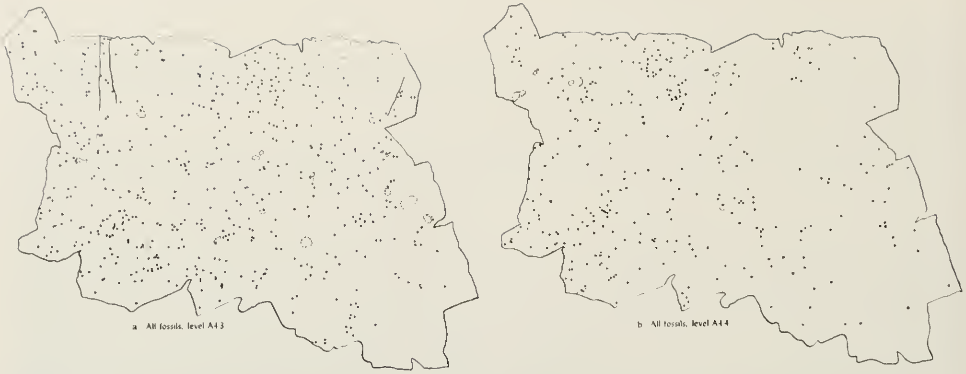
FIG. 30. Rubber cast of lumen of spiral intestine of a modern shark. Cast slightly stretched to show structure. Left end of cast includes rectum, which is not coiled (see discussion, p. 144). (Drawing by Maidi Leibhardt.)

1. The Fossil Content as a Whole

The fossil content enclosed in successive quarter-inch levels generally shows a fairly even distribution of the particles and specimens. Obvious aggregations of particles in one part of the quarry versus another were not noticed at any level. Such differences as may be noted in some levels are due to the more weathered condition of the shale along the outcrop edges of the quarry, and to a minor degree to differences in the charting among assistants (see p. 14).

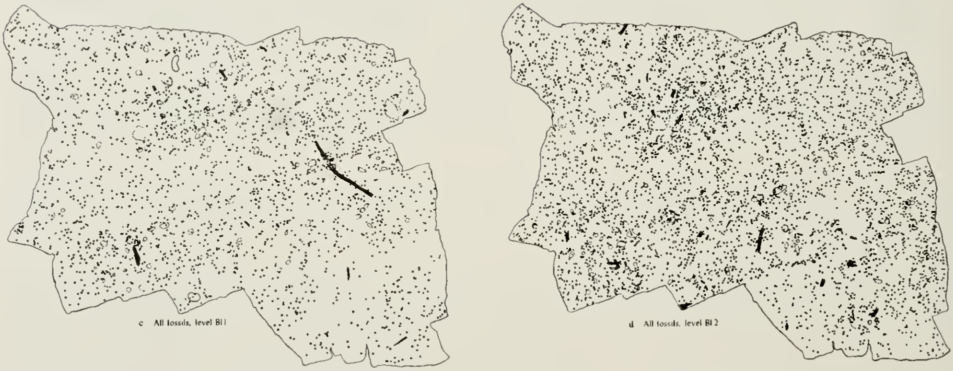
In any given part of the quarry floor, however, the particles often tend to be somewhat grouped together with notable areas of barren shale here and there (fig. 31). In levels with high particle density, for example, B1.2, this grouping is less apparent and the distribution pattern is extremely uniform throughout the quarter-inch level (fig. 31, *d*). A further noteworthy aspect to the distribution of the particles is the even mixture of all constituents, regardless of weight, size and form. In only one instance is there a bunching of driftwood (B1.3) which might represent a minor snag.

The horizontal particle distribution indicates beyond doubt uniform mud bottom conditions and lack of currents strong enough to bring about any sorting of the organic debris (see also pp. 156–161).



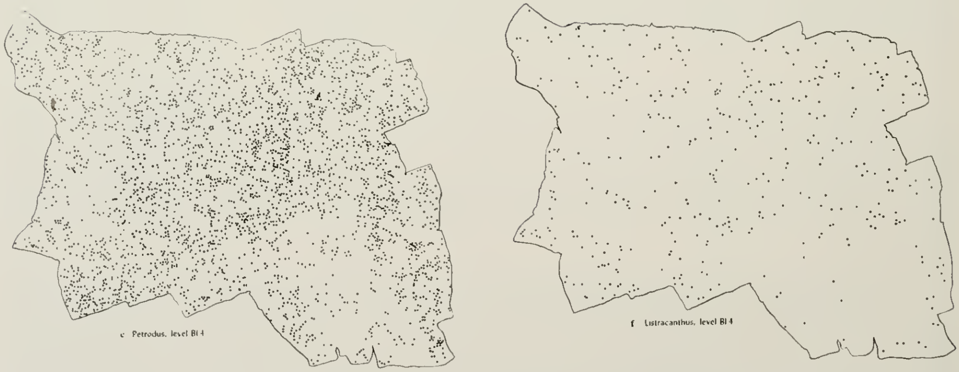
a All fossils, level A4 3

b All fossils, level A4 4



c All fossils, level B1 1

d All fossils, level B1 2



e Petrodus, level B1 4

f Listracanthus, level B1 4

FIG. 31, *a–f*. Horizontal distribution of fossils in Mecca Quarry shale at Mecca Quarry in certain narrowly defined microstratigraphic levels. Charts cover the entire quarry floor, approximately twelve by fifteen feet; north at upper edge. (*a–d*) Total charted faunal debris and driftwood in each of four successive quarter-inch levels. Dotted outlines denote associated skeletal parts or partially articulated specimens. (*e, f*) *Petrodus* placoid scales and *Listracanthus* spines in a single quarter-inch level (see also *g, h*).

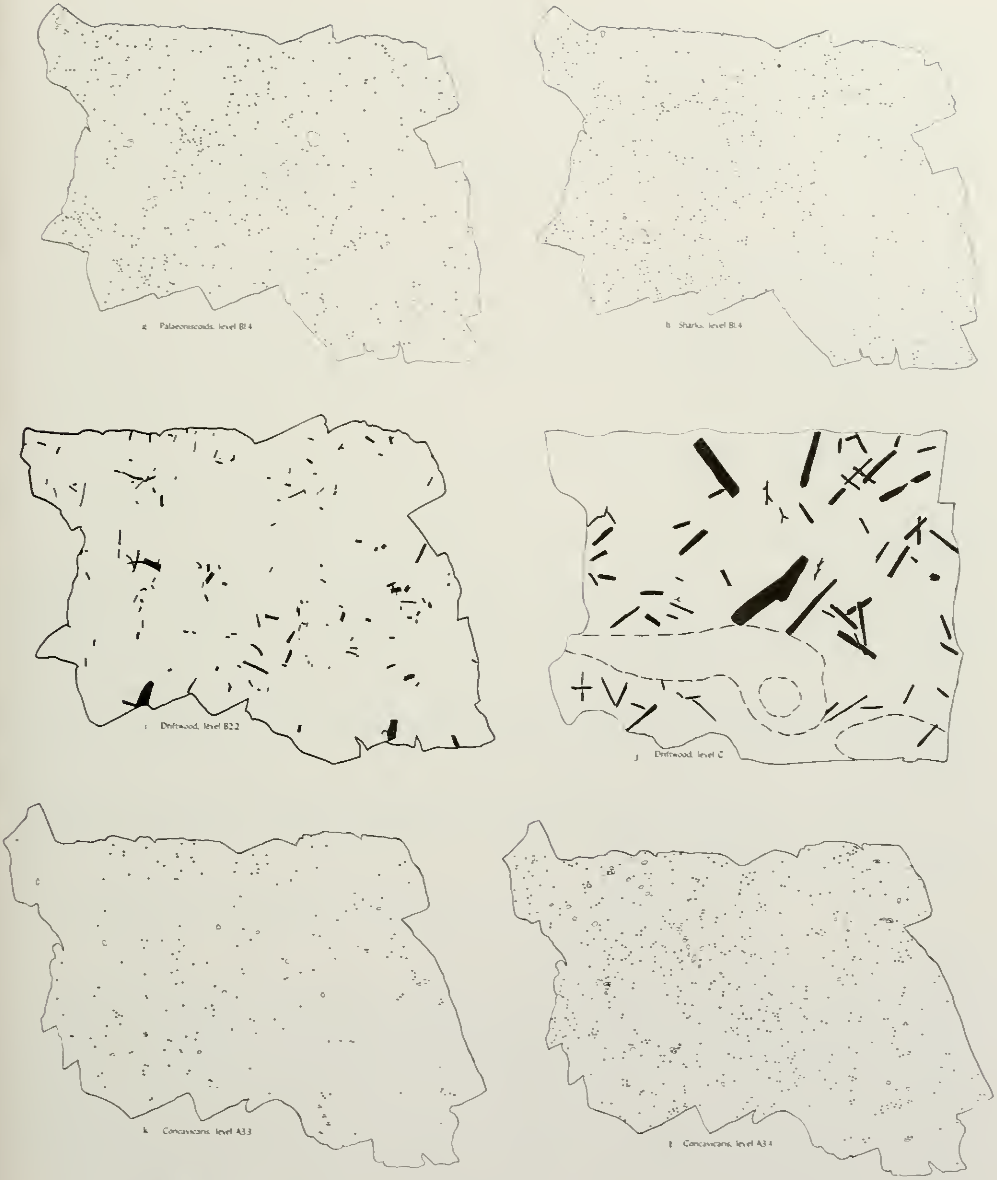

g Palaeoniscoids, level B1.4
h Sharks, level B1.4
i Driftwood, level B2.2
j Driftwood, level C
k Concavicaris, level A3.3
l Concavicaris, level A3.4

FIG. 31 (*continued*), *g–l*. (*g, h*) Palaeoniscoid specimens and debris, and shark specimens and debris in a single quarter-inch level (see also *e, f*). Dotted lines denote associated skeletal parts of partially articulated specimens. (*i, j*) Driftwood in a single quarter-inch level and in level C, 3 inches thick; dashes outline large concretions. (*k, l*) *Concavicaris* specimens and debris in two successive quarter-inch levels.

2. Isolated Particles

Listracanthus: The genus *Listracanthus* is based on small, rather delicate spines belonging to an otherwise unknown fish. It is a characteristic fossil in Pennsylvanian black sheety shales; it occurs frequently together with *Petrodus* denticles (see below). It is noteworthy that where one of these is rare the other is likely to be rare also, for example, in all levels of the Logan Quarry.[1] The size, shape, and delicate structure of these spines indicate that they belonged to fairly small animals; it is probable (but not certain) that there were several spines per individual. The horizontal distribution of these spines is fairly uniform in all levels. Concentrations of spines are absent except in gastric residues, and these are extremely rare. Here and there on the distribution maps one has the impression that several spines (often in sets of three) are close together but where the density is greater such grouping seems to disappear. Furthermore, not all spines charted for a quarter-inch level are on the same bedding plane, so that we are looking at a concentration of spines that accumulated over a period of several weeks. Since *Listracanthus* rarely served as prey in the Mecca area we must assume that they died of other (undeterminable) causes. As their carcasses decomposed they may have floated in the upper, watery part of the mud column, probably drifting with the movement of the ground water over the mud bottom and contributing their spines to the accumulating sediment beneath. In this fashion a chance distribution of the spines would probably result (for a discussion of the orientation of these spines, see p. 156).

Petrodus: This is the generic designation for a characteristic, relatively large placoid denticle (pl. 52) of an otherwise unknown animal.[2] We have no information, therefore, of the size of the animal or the approximate number of denticles per individual. On morphological grounds we are justified in assuming that the creature was an elasmobranch and that the denticles were located on the skin of the animal. Individual denticles of the shagreen were probably shed and replaced in the course of the animal's life, as happens in modern sharks.

Petrodus is widely distributed in black shales of Pennsylvanian age, often representing (together with *Listracanthus*) the only evidence of vertebrate life in some environments in which black shales were deposited.

In shales in which few denticles may be found, as, for example, in all levels of the Logan Quarry, it is probable that they are elements shed from the living animal. In the Mecca Quarry, however, *Petrodus* scales are present in large numbers, ranging from less than 100 (in A4.2) to more than 3300 (in B1.2) in single quarter-inch levels of shale (fig. 32). The horizontal distribution of these denticles over the quarry floor is irregular at all levels. Nowhere in Mecca Quarry were there large accumulations of such scales or patches of shagreen more or less in place. In the absence of obvious environmental mechanisms responsible for the irregular distribution of these placoid scales over the mud bottom it seems probable that the explanation lies wholly with the physical attributes of the animal (its size, and the number of scales per individual) and the circumstances of decomposition. Since both are unknown the following arguments and conclusions must necessarily remain tentative.

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[1] This has led to the suggestion (Bradley, 1870, p. 144) that *Listracanthus* spines and *Petrodus* denticles might belong to the same animal. The vertical distribution of these elements in the Mecca Quarry would seem to rule out such a possibility (fig. 32).

[2] Such associations of denticles with other skeletal elements as have been suggested (Moy-Thomas, 1935) are almost beyond doubt fortuitous.

Because of the relatively large size of the *Petrodus* placoid scales one is tempted to think of *Petrodus* as a large animal bearing a large number of denticles.[1] To arrive at the observed distribution of denticles (both horizontal and vertical) one would have to postulate, under this concept of the animal, ever-present decomposing carcasses, slowly drifting over the burial ground in the Mecca area, peppering the bottom with scales as they came loose from the skin. Such an assumption seems unlikely but remains as a possibility. A different interpretation of *Petrodus* may be gained by the comparison of the distribution of the denticles with that of the *Listracanthus* spines (see above).

These distribution maps are similar in every respect, which may indicate that the animals responsible had certain features in common, for example, similar body size, and a limited number of preservable hard parts. This suggestion is further strengthened by the fact that the two forms are often found in the same localities and often where other vertebrates are absent, indicating that they frequented the same environments. They have in common, furthermore, an interesting ecological status: neither of them regularly served as prey to the predators in the Mecca area.[2]

The mode of decomposition and the spreading (dispersal) of the denticles of *Petrodus* may thus have followed a course similar to that of *Listracanthus*.

Acanthodians, "Placoderms," Sharks and Palaeoniscoids: Debris of acanthodians, "placoderms" and elasmobranchs was charted together because in the early phases of the charting of the Mecca Quarry the vertebrate content was not yet known, and fragments of these forms could therefore not be properly separated during the charting process.[3] Debris of palaeoniscoid fishes, on the other hand, is so characteristic that it could be charted separately from the beginning.

The horizontal distribution of the debris of these animals (fig. 31, *g*) shows much the same pattern as that for *Listracanthus* and *Petrodus*, but there is a difference: In contrast to *Listracanthus* and *Petrodus* all of these animals occur also as partial (and sometimes essentially whole) specimens (see below). While the palaeoniscoid bones are generally whole bones, the cartilage elements of the sharks usually occur as fragments. The mode of dispersal of these particles over the mud floor appears to have been much the same as in the case of *Listracanthus* and *Petrodus*, but their history prior to burial was different. As was shown (p. 139), most of the fossils in this category consist of partially eaten specimens. The parts that were spilled evidently became the loose debris.

3. Partial Specimens

Here and there among the fossil debris of the quarry floor there are aggregations of skeletal elements that clearly belong to single individuals. For the most part these elements are not in articulation with one another, and most often only a partial individual is represented. For example, a palaeoniscoid fish may be represented by a well-circumscribed mass of scales, lacking skull bones; or only the skull bones are present along with a few scales. In the case of sharks the aggregation often consists of a large number of pieces of broken cartilage along with numerous teeth, indicating that the remains of the skull of a shark are

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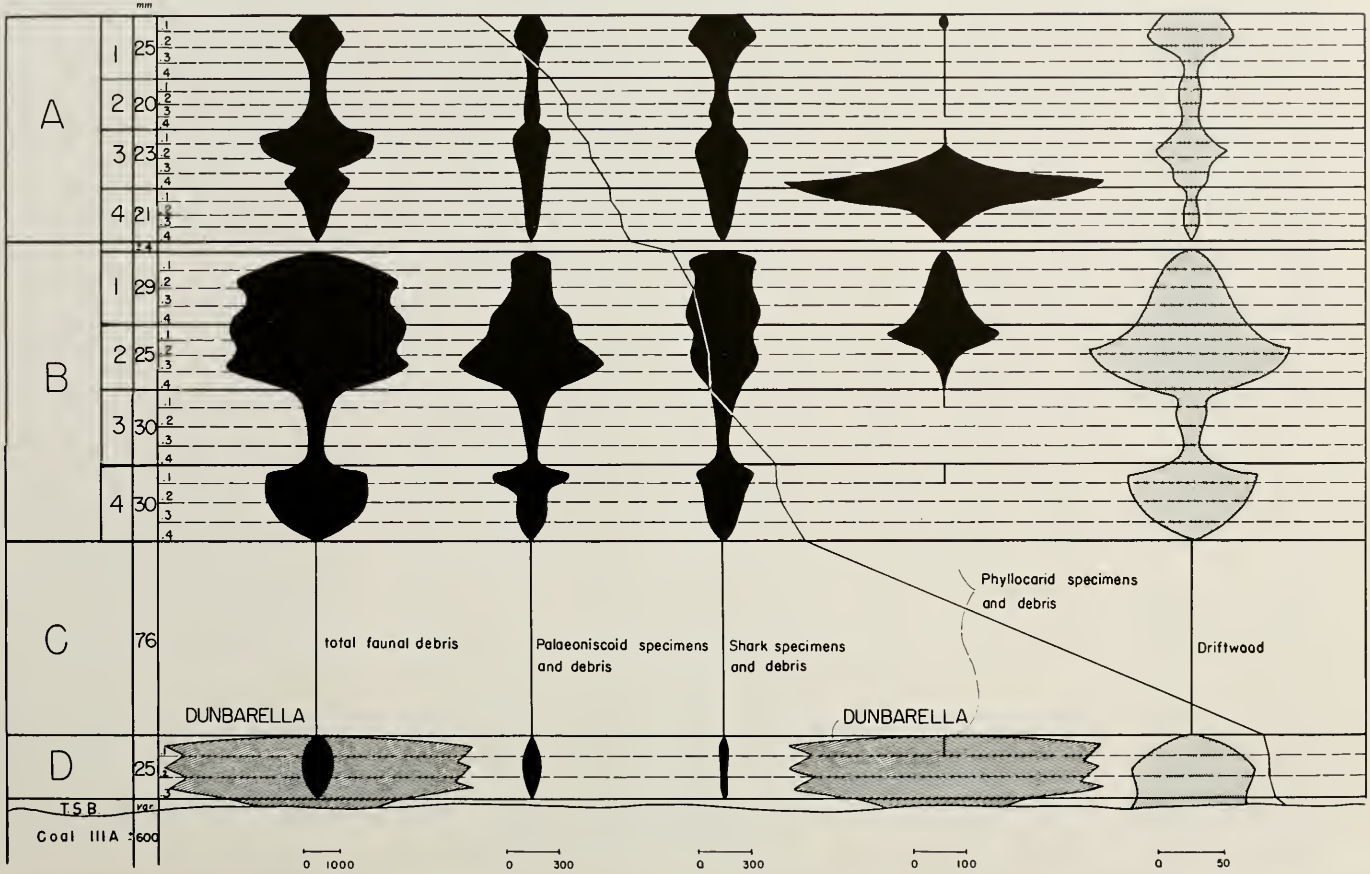
[1] This is not necessarily a valid conclusion. Among modern elasmobranchs it is the moderately sized skates that bear the largest placoid scales, not the whale sharks.

[2] In other localities, however, both are known from very large stomach residues. We must conclude that the animals that preyed on these forms were not present at Mecca.

[3] In the later phases of the charting the three groups of animals were indicated by their correct respective designations.

MECCA QUARRY

Distribution of Faunal Debris and Driftwood



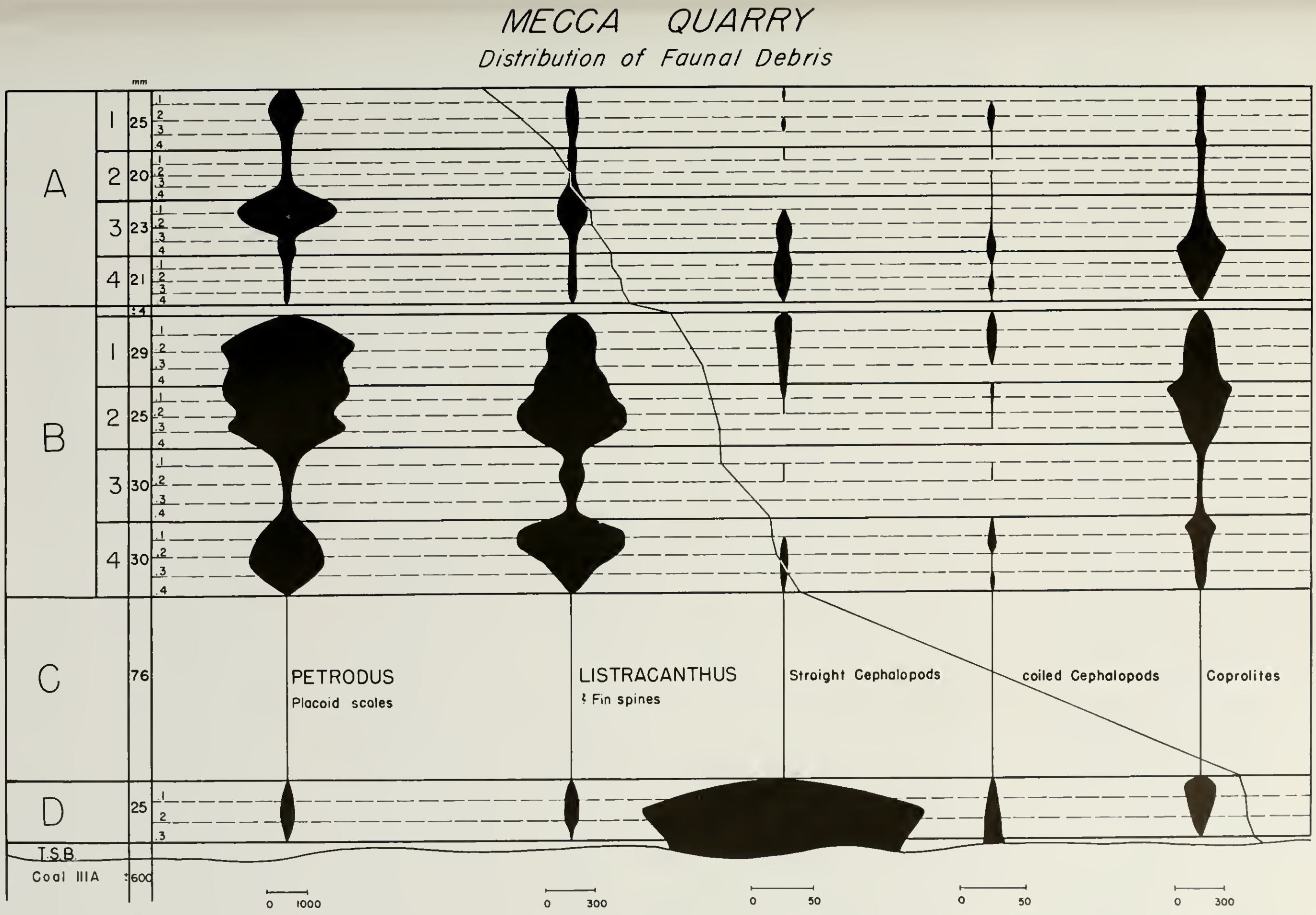


FIG. 32. Vertical distribution of fossil content of Mecca Quarry shale at Mecca Quarry. Width of bars proportional to abundance in each microstratigraphic level, according to scales beneath bars. *Dunbarella* was too abundant and was not counted. Slope of irregular diagonal line indicates relative blackness of levels (see reflectivity measurements, p. 16).

present. Equally often, however, specimens are not fragmented to such a degree; entire cartilage elements may be present among broken ones, and sometimes elements are even preserved in natural articulation.

Such an aggregation of skeletal elements is not merely a local concentration of the debris that littered the mud bottom; it represents the remains of an individual not dissipated before burial. This is particularly evident in specimens that comprise a large portion of an individual in such a way that the major regions of the body (the skull, the abdominal region, the tail section) are clearly discernible, although the bones (or cartilages) are disarticulated. Furthermore, such aggregations contain, for the most part, elements of only one kind of animal.

More rarely, however, two or even three species may be represented in a single aggregation. The skeletal elements are not entirely mixed together. Instead, each species occupies a definite portion of the aggregation and there is some mixing of the elements where the two species are in contact. The individuals comprising such aggregations, furthermore, tend to show differences in the degree of disarticulation and general quality of preservation. Nearly all possible combinations of the elements of the vertebrate fauna were noticed in aggregations of this kind, except for *Petrodus*. Sometimes vertebrates and invertebrates are associated in this fashion. The horizontal distribution of these partial specimens over the quarry floor shows no peculiarities that might be due to factors other than chance.

For reasons set forth (see p. 140) the specimens in this category are interpreted as stomach content that was regurgitated by the predators either soon after ingestion, or after partial digestion.

4. Coprolites

Coprolites in the Mecca Quarry consist of a dark to light brown, earthy, sometimes highly bituminized groundmass, often containing teeth, scales, and bones sufficiently well preserved to be identifiable. A similar earthy material, however, is sometimes associated with gastric residues (p. 140), rendering some of the specimens difficult to classify in unsectioned condition. At the time of the charting of the Mecca Quarry the nature of the fossil content had, of course, not yet been analyzed and for this reason many gastric residues were listed as coprolites. Since coprolites occur in a notable variety of sizes, shapes and colors, similar charting by different persons was difficult to achieve. For this reason some of the distribution maps show conspicuous differences in the density of coprolite occurrence in parts of the quarry floor.

5. Phyllocarids

In those levels in which the phyllocarids are fairly plentiful, their distribution is irregular (fig. 31, *l*); such aggregations of debris as may be seen in some places may represent parts of a single individual or parts of several. Since phyllocarids are included in the intestinal content of some shark specimens from the Logan Quarry, there would seem to be no doubt that this arthropod served as prey for several of the predators and that much of the phyllocarid debris resulted from predator action.

6. Cephalopods

Cephalopods are relatively rare and for this reason their horizontal distribution is not really meaningful. In level D.2, where the density of occurrence is adequate, the cephalopod shells are irregularly dispersed.

7. WOOD

The logs and sticks lying on the quarry floor appear to be more clustered than the animal remains. In some levels sticks tend to be grouped together (for example, in B4.1), often overlapping each other, which might indicate that they were deposited at the same place in succession; or such little aggregations might represent minor snags, as, for example, in B1.3. In levels B2.1, B2.3, and A1.3 there appear to be concentrations of larger sticks in the northwest corner of the quarry. In level B2.4 there is a notably denser accumulation of sticks on the eastern half of the quarry floor. In most levels, however, the distribution is fairly even (fig. 31, *i*, *j*).

b. VERTICAL DISTRIBUTION OF THE FOSSIL CONTENT IN MECCA QUARRY

The vertical distribution of the fossil content in the Mecca Quarry is illustrated (fig. 32). The most noteworthy aspect of the distribution is the periodicity in the density peaks, which coincide closely with the blackest levels of the shale sequence (see also fig. 39). This is especially true for levels D, B4, and B2, and to a slightly lesser degree for A3. The density peaks of the various faunal elements do not always lie exactly in the same quarter-inch levels, and the invertebrates do not follow the overall pattern of the vertebrate distribution. Level D contains countless specimens and fragments of the pectinoid *Dunbarella* up to the D–C contact, but only one small fragment was found above this contact (in level A3.4). The single arthropod, *Concavicaris*, has a very restricted vertical distribution and its density peaks, B2.1 and A3.4, are the same as those of the coprolites. *Pseudorthoceras knoxense* is fairly common in D but so rare above D that its distribution is of no significance nor is that of the coiled cephalopods, except, perhaps, to the extent that they do seem to be more common in the relatively gray levels B1 and A4. Among the vertebrates, *Listracanthus* and the palaeoniscoids reach maximum densities in the same quarter-inch levels and their distribution patterns are very similar throughout. *Petrodus* and the sharks (including "placoderms" and acanthodians) have generally similar patterns, especially in B1 and B2. Driftwood seems to fit the vertebrate pattern very closely.

Since sharks, acanthodians, "placoderms" and palaeoniscoids occur not only in the form of debris but also as partial specimens, and since all of such remains were collected, it is possible to chart these elements of the fauna separately. It is interesting that the vertical distribution of these animals together (without their debris) very closely resembles the pattern of the total debris in the quarry. If each animal group is charted separately, however, their distributions do not coincide with the total, nor do they greatly resemble each other. For example, partial shark specimens are much more common in B1.3 than "placoderms" but the opposite relationship exists in B4.2, and there are no acanthodian specimens in all of A4 and B3. Palaeoniscoid specimens, on the other hand, are very common in B4.1.

These density figures probably provide an idea (however approximate) of the relative abundance of the various groups of animals, in view of the conclusion that their remains probably have random horizontal distribution. However, virtually all specimens recovered from the Mecca Quarry are individuals injured or actually eaten and subsequently regurgitated by the predators (see p. 137). It is thus possible that the vertical distribution patterns of these gastric residues are somewhat modified by food preferences of the predators at times when preferred food was in plentiful supply. For example, it seems unlikely that "placoderms," small sharks, and acanthodians were absent in the Mecca area during the period B4.4 and that the palaeoniscoids were the only source of food (aside from *Petrodus*, *Listracanthus* and the invertebrates).

Since virtually all specimens recovered from the Mecca Quarry have been victims of predatory activity (including the predators themselves)[1] it is interesting to note the fact that stomach residues greatly outnumber the coprolites (fig. 42).

c. REGIONAL DISTRIBUTION IN MECCA QUARRY SHALE

The Mecca Quarry shale was not sufficiently sampled regionally to permit a satisfactory quantitative treatment of this aspect. Such sampling as has been done, however, shows beyond a doubt that the fossil content is not distributed uniformly in the area of study. There are areas of vast fossil concentrations such as at Mecca Quarry, and others where the shale is essentially barren (as at Barren Creek).

We noted that localities where the Mecca Quarry shale was extensively exposed produced fewer fossils than sites of limited outcrop area. This observation is the opposite from what might have been expected, since extensive outcrops permit examination of larger amounts of shale.

The fact that both the Mecca and Logan Quarry shales form extensive outcrops in some localities, but very limited ones in others, seems to be related to a difference in the petrographic composition of the shale. In large outcrops the shale tends to be more highly carbonaceous, containing a lesser amount of clay; hence it is harder and more brittle and has less perfect horizontal splitting characteristics; hence it is more resistant to weathering.

It seems to us highly probable that there is a relationship between the petrographic composition of the sheety shales and the relative burial density of the fossil content. Microscopic examination (p. 105) shows that flaky plant decomposition products form a large proportion of the shale's composition; we have come to the conclusion that most of this plant material originated from a floating plant cover (*flotant*, p. 121). Scarcity of clay indicates that such areas received little turbulent water. It seems very likely, in view of all the rest of the evidence presented in this paper, that the *flotant* was nearly in contact with the bottom mud at such points, thus filtering out the clastics and preventing the animals from reaching these areas. Hence the concatenation of shales with little clastic material and little fossil content.

d. HORIZONTAL AND VERTICAL DISTRIBUTION AT LOGAN QUARRY

The horizontal distribution of the fossil content was not recorded at Logan Quarry. The following account must, therefore, be based on observations, made during the quarrying operation, that are believed to be valid.

The vertebrates at Logan Quarry were very probably not buried in a random distribution. It was noted that there were appreciable areas of all but barren shale, and others where it proved difficult to separate the specimens. For example, we did chart a suite of six specimens in the immediate vicinity of the large shark (PF 2201, pl. 24, B) in level J. These six specimens surrounded the big carcass on its south side; none were north of it. The Logan Quarry subsequently was extended northward from the large shark, and we noted that level J was barren for a distance of several yards north of that fossil, where there again appeared to be an aggregation of specimens.

The giant coiled nautiloids in level F seemed to be spaced fairly evenly about 4 to 6 feet apart in all directions. This distribution should have been charted, because we gained the definite impression that their horizontal distribution coincided with the location of large ovoid calcareous concretions in level H beneath. Unfortunately, much of the quarry had been excavated by the time we realized this apparent relationship.

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[1] The small size of the stomach residues at Mecca Quarry indicates that the major predators were not large.

The vertical distribution of the fossil content is on record, since we collected the fossils encountered.[1]

The large coiled nautiloids were most common in level F; only a very few were seen in level G. The goniatites, on the other hand, were found only in level G.

The vertebrates occurred in all levels, but only in levels J and G in appreciable burial density. The acanthodians were most abundant on a single bedding plane covered with debris and tufts of fecal material, in the lower half of level J.

e. REGIONAL DISTRIBUTION IN LOGAN QUARRY SHALE

The burial community of the Logan Quarry shale differs a good deal from one locality to another. Three distinctive thanatocoenoses may be recognized, two of which are associated with black sheety shales, the third with a humulite.

At Logan Quarry, South Collings Creek and Trumpet Valley the burial community of the sheety shales is essentially a marine vertebrate assemblage, accompanied by a minor suite of marine invertebrates; at Big Pond Creek and Haworth Creek it is almost entirely molluscan. The burial community of the humulite at Garrard Quarry and elsewhere represents a fresh-water assemblage of invertebrates and vertebrates, most of which are restricted to this facies.

The sheety shales of this horizon at Barren Creek, like those of the Mecca Quarry shale, contain virtually no fossils.

f. VERTICAL AND GEOGRAPHIC DISTRIBUTION OF THE MECCA FAUNA

The Minshall to Velpen limestone interval studied in the general area of Parke County, Indiana, contains, besides the Mecca and Logan Quarry shales, other transgressive sheety shale horizons (pl. 55), namely, the black shale overlying coal IIA and the Holland black shale (Table 2). Neither of these has been prospected along its outcrop belt, but they have been investigated briefly at some localities. Both contain the Mecca fauna, the IIA shale at Coal Creek, and the Holland black shale at South Collings Creek and at Mine Creek.

The Mecca fauna thus extends practically through the entire stratigraphic interval and it seems reasonable to suppose that it extends both higher and lower in similar transgressive sheety shale facies.

The geographic distribution of the Mecca fauna throughout the Illinois Basin and beyond remains to be determined. We have some evidence of its presence along the western fringe of the Illinois Basin near Galesburg, Knox County, Illinois, a locality that has produced some vertebrate remains of similar character to those from Parke County, Indiana.

We have recently seen most elements of this fauna in newly opened strip mines in Kankakee County, Illinois. A facies similar to the black Garrard Quarry humulite (Zone 4) was also seen in this area, with the fresh-water fauna.

Elsewhere in the Illinois Basin there are numerous reports in the literature of *Petrodus*, *Listracanthus* and occasional palaeoniscoid remains. Whether these localities contain the entire Mecca fauna remains uncertain.

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[1] Isolated debris, some gastric residues and coprolites, and most of the badly flattened large cephalopods were not collected.

g. DIRECTIONAL PROPERTIES OF THE MECCA QUARRY SHALE

By
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The following is an expansion of a paper entitled "Speculation on water currents in a black shale environment, by use of orientation and dispersion of fossil fragments," given at the 1956 meeting of the American Geophysical Union (Miller, 1956).

The Mecca Quarry shale exhibits none of the more common diagnostic, directional properties, such as cross-bedding or current markings. In addition, the surfaces studied were considered too small for reliable interpretation of trends in, for example, sediment or fossil particle size. The area of a given plane did not exceed 12 x 15 feet. Therefore, attention is focused on two available properties, orientation of individual fossil fragments, and the less commonly considered dispersion over a plane[1] (fig. 34).

Analytic procedure: Two problems are considered. The first is to ascertain whether a preferred orientation exists in suitably elongated particulate matter for a given layer. The second is to ascertain whether the distribution of suitably chosen particulate matter over a plane in a given layer is random. If not, two contingent possibilities are considered: either the particles are clustered, or they show mutual repellance. These terms will be defined and expanded in the following.

1. Orientation

A useful measure of orientation in the present context should include a measure of direction and of "strength." Orientation is defined here to be an alignment of long axes of the material of interest such that a resulting angular summation expression (an average, mode, or vector resultant) differs statistically from the expectation under a uniform distribution. The uniform distribution is taken to be the model for a random distribution, in which the probability that a given long axis has a particular direction is the same for all directions. If the angular summation varies significantly from the uniform model, the conclusion is drawn that a significant orientation exists. The direction and "strength" of the orientation are then of interest.

A discussion of uniform versus random distributions in the present context is found in Pincus (1953) and Curray (1956). The choice of suitable elongated material for study was based on size, availability and possible ecological implications. In level B3 (fig. 2) *Listracanthus* spines and wood fragments were used; in level C wood fragments and straight cephalopods (*Pseudorthoceras knoxense*) were used.

The *Listracanthus* spines (fig. 33, *b*) are discussed elsewhere in this volume (p. 148). The spines vary from 1½ inches to as little as ⅛ inch along the long axes, and consist, geometrically, of slightly curved, elongate, tapered blades with narrowly elliptical thickened bases.

The wood consists of pieces of stems varying from about 3½ feet to 3 inches in length. Only strongly elongate pieces were used, with length-width ratios varying from 6:1 to greater than 10:1.

The cephalopod, *Pseudorthoceras knoxense* (fig. 33, *d*), is a conical, straight-shelled form with heavy cameral deposits in the apical region of the shell; in life it presumably swam and floated horizontally. Death not due to predation would probably not be an instant event,

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[1] For an application to contemporary marine intertidal invertebrates see Johnson (1959).

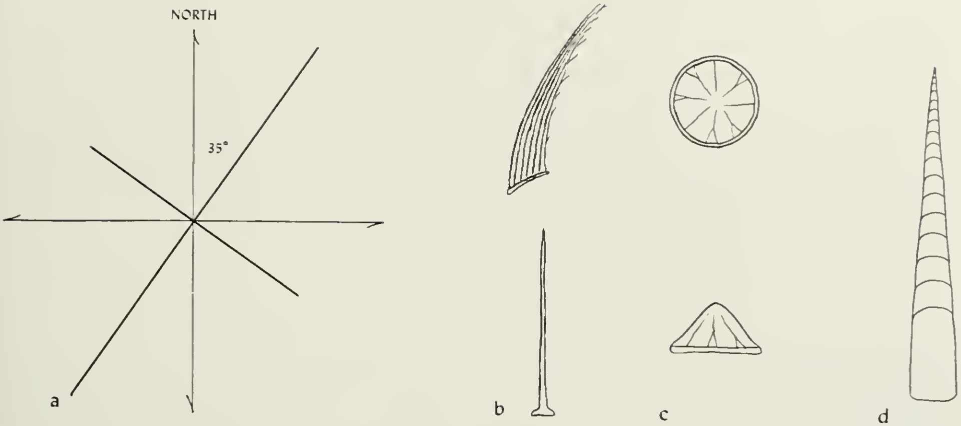
NORTH
35°
a
b
c
d

FIG. 33. (*a*) Orientation of driftwood in level C, Mecca Quarry shale, Mecca Quarry. (*b–d*) Shapes of particles used in analysis of orientation and spatial distribution: (*b*) *Listracanthus* spine in side and edge view; (*c*) *Petrodus* denticle in top and side view; (*d*) side view of straight cephalopod shell, *Pseudorthoceras knoxense*.

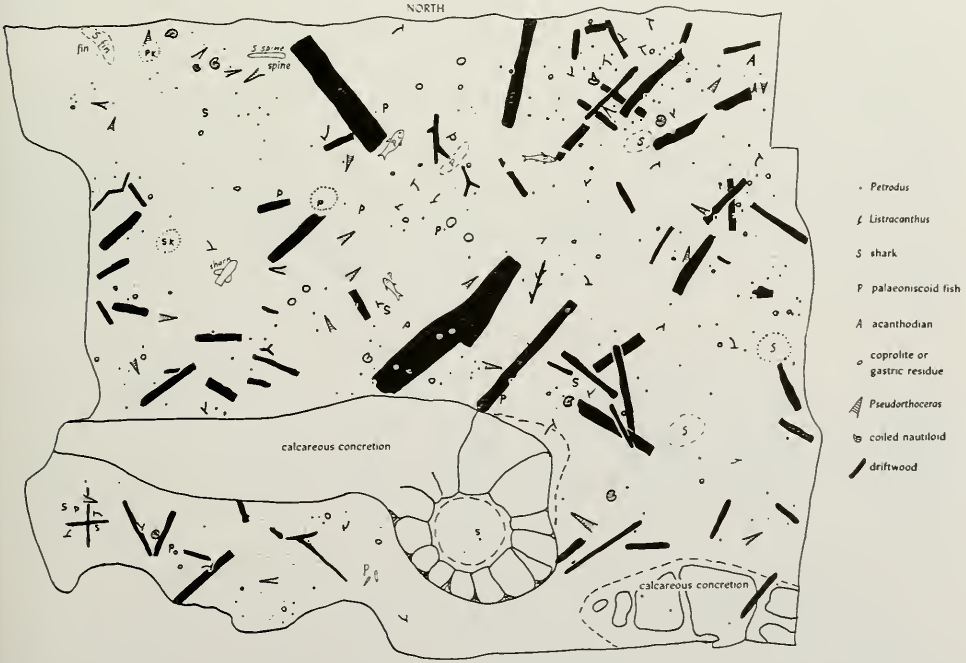
NORTH
fin
spine
calcareous concretion
calcareous concretion
Petrodus
Listracanthus
shark
palaeoniscoid fish
acanthodian
coprolite or gastric residue
Pseudorthoceras
coiled nautiloid
driftwood

FIG. 34. Chart of fossils and large concretions in level C, Mecca Quarry shale, Mecca Quarry. Elongated objects are shown in correct orientation.

so that the moribund would very likely be oriented by a water current while sinking to the burial site. It is unlikely that the shell would strike the bottom on either its apical or its apertural end. A shell broken by a predator might be expected to sink rapidly to the bottom, deprived of the buoyancy of the soft parts. Thus the only shells likely to exhibit current orientation in the case of very slight currents are those of animals dying a natural death within the water column, by asphyxiation or by salinity change. Once a shell has come to rest upon the settling surface, a fairly appreciable current must be required to alter its initial orientation, unless gases, developed during aerobic decay, should sufficiently lift the apertural end to raise it above the frictional restraint of the bottom.

The dimensions are from 3 to 4 inches in length and about ⅜ inch across the bases of the cones.

Significant range 180° versus 360°: In those cases where there is no "sense" to the long axis the range of 180° is suitable for the recording of orientation; for example, under unidirectional fluid flow a homogeneous cylindrical rod may line up parallel to the fluid flow lines. However, there is no tendency inherent in the geometry of the rod itself, for a particular end to point, say, upstream. Therefore, either end may be used and the angular variation is completely described over a range of 180°. On the other hand it may be thought that an elongate cone will have a tendency to point its apex into the direction of flow so that the base faces downstream. Thus the direction in which the apex is facing in the shale is significant over the full 360° range. In other words there is "sense" to the long axis.

In the case of the wood particles the 180° range was used. For the straight cephalopods and the *Listracanthus* spines both the 180° and 360° ranges were tested, because of uncertainty as to the reaction of these shapes to fluid flow.

Method: It is inappropriate in this short paper to give in detail the analytical method. Curray (1956) gives a full exposition. In brief, the long axis is considered as a vector with a given direction and, for convenience, unit magnitude. The north-south and east-west vector components are recorded from the summed individual azimuth data weighted by the sample size. The resultant vector is computed to give the vector strength (L). Then for given L and sample size N, Rayleigh's (1894) test of significance is applied. Table 4 of Curray (1956) conveniently graphs the significance test for vector magnitude L as a function of sample size N.

TABLE 7.—ORIENTATION RESULTS FOR LEVELS B3 AND C

	Listracanthus			Wood Fragments		Cephalopods		
Level	360°	180°	N	180°	N	360°	180°	N
B3.1	N.S. (R)	N.S. (R)	94	N.S. (R)	20	—	—	—
B3.2	N.S. (R)	N.S. (R)	73	N.S. (R)	22	—	—	—
B3.3	N.S. (R)	N.S. (R)	60	N.S. (R)	12	—	—	—
B3.4	N.S. (R)	N.S. (R)	167	N.S. (R)	16	—	—	—
C	—	—	—	N.S. (R) (see text)	67	N.S. (R)	Signif. (R)	26

N = sample size.
N.S. (R) = no significant orientation, using the Rayleigh test (Curray, 1956).

The frequency distribution of wood fragments in level C indicates a strong bimodality with a major peak at N. 35 E.–S. 35 W. and a secondary peak 90° from the major peak (fig. 33, *a*). It is possible that this is a function of the geometry of the wood under a unidirectional flow. Flume observations on other material have indicated a tendency for rod-like forms to align themselves either parallel to the flow or (to a lesser degree) at right angles to the flow. Some experimental work on azimuth frequency distributions of geometric shapes under unidirectional flow would be quite useful.

2. Spatial Distribution

In this section, the interest is focused on the redistribution of animal remains after death. Factors which are considered are those forces that act on the animal remains from the time of death to the time of final deposition of the individual fragments. For example, the animal may be floating, and upon deterioration release various preservable hard parts. These will be acted on by the downward force of gravity and by the lateral and lift forces of the fluid, when a velocity exists.

We can only infer the initial position of the hard parts—on the bottom or floating—before their final distribution over the sediment–water interface.

The formal model for random distribution of points over a plane is given by Clark (1956). A full discussion of the consideration of reflexive relations between "nearest neighbors" and of the general problem of spatial distributions is given in Miller and Kahn (1962, chaps. 16, 17); included are suitable tables and a flow sheet for computation.

In practice the results are compared with the expectation for a random distribution. If the results are consistently higher than the expectation, there is inferred a tendency toward clustering of points. If the results are consistently less than expectation there is inferred a tendency for mutual dispersion of points.

In the present study three types of particles were analyzed:

1. Placoid scales of *Petrodus* (fig. 33, *c*). These are the dermal denticles of the otherwise unknown shark *Petrodus*. The denticles are in the shape of very low-angle grooved cones about ¼ inch high with a circular base about ⅜ inch in diameter.

The question of size of *Petrodus* is discussed (see p. 148). Suppose the animal floated after death, and the dermal denticles separated over a time from the carcass and fell to the bottom. With a reasonable drift, the resulting distribution of the scales on the bottom might be expected to be random; if, on the other hand, the carcass rested on the bottom before losing its denticles, an expectation of clustering would seem reasonable; see more detailed discussion of this matter (pp. 148–149).

2. *Listracanthus* spines. An argument may be used here similar to that given for *Petrodus*. Clearly other possibilites exist.

3. Cephalopods. A clustering effect could be caused by gentle vortices or eddies in the water regime. Since the number of possible events is at least as large as in the previous cases, one can only speculate. Table 8 summarizes the results of analysis of the distribution of *Listracanthus* spines, *Petrodus* scales and cephalopod shells in various microstratigraphic levels.

Table 8.—SPATIAL DISTRIBUTION OF *LISTRACANTHUS* SPINES, *PETRODUS* SCALES AND CEPHALOPOD SHELLS TREATED AS POINTS ON A PLANE

Level	*Listracanthus* spines	*Petrodus* scales	Cephalopod shells
B3.1	clustering N=101	clustering N=415	not present in sufficient numbers
B3.2	clustering N=163	clustering N=242	
B3.3	clustering N=89	not done	
B3.4	clustering N=38	clustering N=225	
C	—	—	random N=26

Discussion and conclusions: From the above described analyses, inference is made regarding the water current direction and magnitude at the time of deposition. It is necessarily confined to the areas studied, but may be reasonably extrapolated over wider areas marginal to these.

Level B3 consisting of four sublayers will be considered first. Both *Listracanthus* spines and the *Petrodus* scales exhibit a clustering effect in all four sublayers. The size of the clusters in no case approximates the size of the parent animal unless the animal was small and bore only a few large denticles, as do some modern skates (see also p. 149). The following lists some possible explanations for the clustering effect in either quiet water or in water of appreciable unidirectional velocity, in the context of the Mecca Quarry shale.

No Current	*Appreciable Unidirectional Current*
1. Pieces of the shark *Petrodus* or of *Listracanthus* came to rest on the bottom followed by decomposition and release of scales or spines, in place.	1. After the material came to rest on the bottom, sediment transport resulted in lag deposits of scales and *Listracanthus* spines.
2. The floating carcass or pieces of carcass released the spines or dermal denticles during an early decomposition stage. These sank directly to the bottom, creating images or shadows of the carcass or pieces.	
3. Predators spat out the hard parts in clumps which then sank to the bottom.	

In view of the lack of complementary evidence of current such as scour or rill marks, etc., the lag deposit explanation is discounted. The hypothesis of quiescent water is taken as best. There is slim likelihood that the floating source remained afloat long enough and in one place long enough to create a "shadow" of spines or denticles on the bottom. *Petrodus* scales were never, and *Listracanthus* spines were but very rarely encountered in gastric residues at Mecca Quarry. Thus explanation 1 under "No Current" seems most reasonable. Conclusion: the water was quiet during the time of deposition of level B3. Currents, if present, were very slight or variable.

Level C presents a contrast in the orientation analysis. The discussion accompanying Table 7 indicates the possibility of appreciable current activity in either a northwest or a southeast direction. This is borne out by the orientation of a geometrically different form, the cephalopods, which indicate a significant orientation in a north or south direction. In this case it is interesting to note that although no significant orientation occurs when the cephalopods are treated as having a "sense" (360° range), a significant orientation is noted when the cephalopods are treated in the same manner as the wood. In view of the vector resultant nature of the orientation analysis the north-south result for the cephalopods agrees well with the N. 35° E.–S. 35° W. orientation of the wood. The random distribution of the cephalopods is consistent with the inferred presence of current in level C and with the argument previously advanced for level B3.

The magnitude of the current in level C is thought to be moderate, and of a fairly consistent direction over the areas studied. A contemporary analogue could be a shallow, enclosed basin with a wind-driven circulation pattern such that the resulting water circulation is fairly consistent over the period of deposition of level C.

This conclusion is valid only to the extent that evidence from the fossil remains, sediments and the local stratigraphy does not contradict it.

H. THE RATE OF DEPOSITION OF THE MECCA QUARRY SHALE

The interpretation of the ecological relationships of the Mecca and Logan Quarry shales depends to a very large measure on our ability to estimate the rates of deposition of the mud and thus the time required for the deposition of the black shale sequence. Slow, moderate or fast rates of deposition of the mud would require entirely different interpretations to account for the character of the shale and the vast accumulation of fossil vertebrates in it.

A variety of methods for the determination of rates of deposition of modern sediments has been proposed; a summary of these may be found in Kuenen (1950, pp. 376 ff.). These results are of interest for comparison with our own determinations below. Estimates as to the rates of deposition of rock sequences, on the other hand, are based on indirect evidence, namely, the similarity between depositional cycles and known astrophysical, meteorological and biological cycles (for an extensive study of this sort, and literature, see Korn, 1938).

The Mecca Quarry shale shows beyond doubt cyclical deposition as determined by microscopic methods (p. 110; fig. 25) and by reflectivity measurements (p. 17; fig. 5). However, the alternate bedding of gray and black layers is not as sharply delimited and not as regular as it is in succeeding lithologic units of typically varved sequences. It is, in fact, impossible to tell from these curves the probable temporal magnitude of the cycles.

It was obviously necessary to devise a method capable of measuring absolute time more directly. The underlying principles of the method applied to the Mecca Quarry shales have, to our knowledge, not previously been used to determine rates of deposition.

1. *The Basic Principles of the Method*

The method here presented is a relatively simple one; it utilizes the processes that determine the fate of vertebrate animals from death to burial. Perfect preservation of a vertebrate skeleton under water is the result of an almost critically balanced interplay between physical and biological circumstances and processes. For this reason the method yields very reliable results, but has only very limited applicability, namely, in exceptionally favorable situations such as present themselves in the Mecca Quarry shale.

(a) THE VERTEBRATE BODY AND ITS MODE OF DECOMPOSITION

Vertebrates possess internal skeletons consisting of large numbers of skeletal elements connected with one another by a variety of forms of connective tissue. After death, bacterial decomposition reduces first the soft parts of the body (epithelial, muscle, connective and nervous tissues); the denser and more resistant skeletal elements (cartilage, especially calcified cartilage, bone, teeth and scales) lose their mutual relationship within the body and become disarticulated. If the degradation process is permitted to proceed, only the most resistant parts (teeth, some scales, spines and otoliths) remain and even these may be destroyed eventually. The following method utilizes only the initial stages of decomposition before the bones become dissociated.

Two notably different decomposition processes are distinguished (Deecke, 1923; Hecht, 1933; Müller, 1951, and others): degradation in the presence of oxygen (aerobic decomposition, *Verwesung,* decay), a relatively rapid process that leads to complete destruction of the vertebrate body; and degradation in the absence of oxygen (anaerobic decomposition, *Fäulnis,* rotting), which requires a long period of time even for the destruction of the soft tissues.

It is generally held to be the only mode that results in fossil preservation of intact vertebrate skeletons.

Studies concerning the fate of vertebrate animals after death are not numerous, many aspects of the problem requiring further investigation, but there are two extensive studies that deal exclusively with this subject, Weigelt (1927) and especially Hecht (1933). Hecht conducted experiments on under-water decomposition of fishes in aquaria and in the Jade-Busen near Wilhelmshaven, Germany. He studied aerobic as well as anaerobic conditions, the chemistry of decomposition of albumen and fat, the role of the sediment in the decomposition process and many other aspects of the problem.

(b) THE SPEED OF AEROBIC DECOMPOSITION

The process of bacterial decomposition begins at the moment of death. Since the environment in which the animal lived undoubtedly contained some oxygen and since entirely stagnant, poisonous bottom waters are apparently rare the degradation process starts with (aerobic) decay. The time required for the decay process to reach the state in which the skeleton of a fish (for example) becomes disarticulated is of particular interest in this connection. Hecht (1933) permitted fresh dead fish to decay in open aquaria. He failed to record the temperature of the water during the course of the experiments, a serious omission in view of the fact that it is the temperature above all other factors that determines the speed of degradation. Since these experiments were conducted at the Forschungsanstalt für Meeresgeologie und Meerespaläontologie "Senckenberg" near Wilhelmshaven on the North Sea, it is probable (but of course by no means certain) that the temperatures were below 20° C.

Hecht's figures are as follows:

Aquarium tank, about 50 liter capacity, open.
Experimental animals: young, dead (presumably fresh) Gadidae (size not specified).
Sea water (s=2.87%), temperature not recorded.
After 4–6 days: carcasses floated near surface with bellies facing upward.
After further 2 weeks: soft parts badly decomposed, skeleton no longer held together, sank to the bottom; skull bones were disarticulated.
After another 2 weeks: all soft parts had completely disappeared.

Other experiments with eels produced similar results, but the carcasses did not float. The speed of aerobic decomposition to the state of complete disarticulation of the skeleton was thus about one month. Hecht points out that this is somewhat slower than might be expected under natural conditions, because the decaying carcass poisoned the tank water during the first half of the decomposition process. Under ordinary natural conditions the water would but rarely be absolutely stagnant and much larger quantities of water would be available.

Hecht's experiments in concentrated (34.4 per cent) sea water; other conditions as above:

Decay process greatly retarded. For three months next to no visible change, then rapid disintegration of soft parts. No principal differences from previous experiment, merely delayed action of the decomposing bacteria.

Hecht's experiments in H_2S-containing sea water; other conditions as above, except that young sharks (*Galeus vulgaris*) were used (size not specified):

Anaerobic conditions greatly retarded the degradation process. Even after one year there were apparently unchanged soft parts (muscle tissue with fine structure) present. At this time the tank water was oxygenated from above. Even so the external appearance of the carcass changed only insignificantly. After 6 more weeks the carcass was disturbed and collapsed instantaneously (see Hecht, 1933, p. 180).

While Hecht's experiments established the order of magnitude of aerobic decomposition speed, his failure to record the temperature and the size of the experimental animals coupled with the fact that these were aquarium tests, renders the values unsatisfactory for our purposes. In order to check his results with experiments in natural situations we asked a number of persons to make decomposition tests in a variety of situations. The methods employed were the same as for our own experiments in Louisiana (see p. 168).

1. Test carried out by Edward and Phillip Huneke at Priest Lake, Idaho (Lat. 48° 34′). This is a deep, very clear mountain lake with rocky, pebbly bottom covered with algal slime. The experiment was conducted between August 15 and September 5, 1956. Four cages with squaw fish (*Ptychocheilus* cf. *oregonensis*), each weighing about ¾ lb., were set out at depths varying from 3 to 20 feet. The temperature at all depths was 19° C. The correspondents report their findings as follows:

> After 1 week: little change, some discoloration of the skin; deeper samples showed less discoloration than shallow samples.
>
> After 2 weeks: in shallow sample the bones had disarticulated. In the two samples of intermediate depth the heads had disarticulated, the bodies were on the verge of falling apart. In the deepest sample only the head had become dissociated; the body was intact.
>
> After 3 weeks: shallow sample completely decomposed. One of the specimens at intermediate depth was missing, the other had the bones dismembered; some skin and intestines left. In the deep sample about half the fish had decomposed; there was a large piece of flesh without skin at the bottom of the cage.

This experiment indicates that the depth of water is a factor of significance, at least when the temperature is relatively low. In view of the findings of Hecht (1933) it is likely that there was somewhat less oxygen available to the deeper samples than to the shallow ones. The lake, furthermore, is wind-swept and this produced better aeration near the surface and removed the poisonous decomposition products from the vicinity of the carcasses.

2. Test carried out by John McLuckie in one of the strip-mine ponds in Will County, Illinois (Lat. 41° 20′), between October 10 and November 24, 1956. The bottom conditions are not described; neither was the depth of the water recorded at the site of the test. A large-mouth black bass (*Macropterus salmoides*) 10 inches long and weighing 10 ounces was used. Mr. McLuckie recorded water temperatures on 15 days during the experiment and these range from 20° C. to 3.5° C. (average 14.5° C.), whereupon there was ice on the surface and the experiment was discontinued. Photographs were taken of the contents of the cage at that time. The fish was in an advanced state of decomposition after 45 days but the photographs indicate that the soft tissues had not yet completely decomposed.

It is highly probable that the low temperatures retarded the degradation process; but there may have been other contributing factors, such as relatively stagnant bottom water.

3. Tests at South Westport, Massachusetts (Lat. 41° 34′) were made by Cameron Gifford during late summer, 1956. He chose a shallow tidal lagoon in marsh country and supplied photographs of the area. The description of the bottom is as follows: top, several inches of mud mixed with sand; beneath this there is black muck. The tides in this area are 3 feet. The low water temperature measured was 22.2° C., the high 24.5° C. Gifford used butter fish (*Poronotus triacanthus*), weighing ¼ pound each. After 7 days fishes had disintegrated except area around vertebral column. After 10 days skeletons were completely disarticulated; no flesh was present.

These figures agree well with those of our own experiments in Louisiana (p. 169), if one considers the slightly lower temperatures at South Westport and the smaller size of the fishes used. If the results of these experiments are summarized in terms of time elapsed from beginning of tests to the stage at which disarticulation of the bones begins the following picture emerges:

	Salinity	Temperature range (Centigrade)	Temperature average (Centigrade)	Weight of fish (ounces)	Depth of water (feet)	Days elapsed from start to disarticulation of skeleton
Hecht (1933), 50 liter aquarium	2.87%	?	?	?	?1	14
Priest Lake, Idaho	fresh	19		12	3 20	14 21
Strip-mine pond, Illinois	fresh	20–3.5	14.5	10	?ca.2	45
South Westport, Mass., tidal lagoon	salt	22.2–24.5	23.3	4	3–6	7–10

These figures indicate clearly that aerobic decomposition of vertebrate animals is a fast process, even at temperatures below 20° C., and its speed increases very notably from 20° C. upward (see also p. 169).[1] The vertebrate skeleton, in fully articulated condition, has thus no chance of survival as fossil unless a nearly anaerobic environment is formed around the carcass soon after death of the animal; under natural conditions this means burial during the initial stages of decomposition by a mat of sediment.

(c) THE ROLE OF THE SEDIMENT IN THE PROCESS OF DECOMPOSITION

The sediment serves a dual function: it shields the carcass against undue access of oxygen and it holds the skeletal components in proper position during the period of gas release and after the soft parts have disappeared. Hecht's (1933) experiments have demonstrated that an aerobically decomposing carcass in a confined situation will poison the immediate environment so that the process of degradation becomes anaerobic. It is very probable that this happens when a carcass is quickly covered by a layer of sediment, in a quiet situation. If the sediment is a highly organic muck, it tends to further diminish the availability of oxygen, hastening the establishment of anaerobic conditions around a carcass.

The different effects of the aerobic and anaerobic decomposition processes are particularly well illustrated by gastric residues and coprolites. In the sheety shales the upper surfaces of such objects are always characteristically flattened and irregular. Sulfides are concentrated along the surfaces of the masses and small bodies of sulfides are seen within the shale in the immediate neighborhood (figs. 35 and 36).

In the very highly pyritic humulites, gastric residues and coprolites are not flattened above and the associated sulfides form large, irregular masses within; in the vicinity of these masses there are no sulfide (sphalerite) bodies comparable to those near the sheety shale specimens (fig. 35, *f*, cf. *c*).

Comparison of specimens in sheety shales with those in the humulite suggests that in the burial environment of the former the specimens were subjected to an initial phase of

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[1] The size of the decomposing carcass appears to have little effect upon the length of time required for the decomposition of the soft parts, as would appear from the following observation, kindly communicated to us by Mr. Wayne King, formerly of the University of Florida. "A specimen of *Mola mola* was caught February 21, 1961, at the mouth of St. Johns River, Duval County, Florida, and was kept in cold storage until February 23 when it was butchered. Original weight was 1400 lbs. After removal of skin and viscera the estimated weight was 800 lbs. This amount was placed in several 55 gallon drums which were filled with water (water temperature approximately 32°C.). The remains were washed and dried on March 4; after only 9 days the skeleton was almost totally macerated."

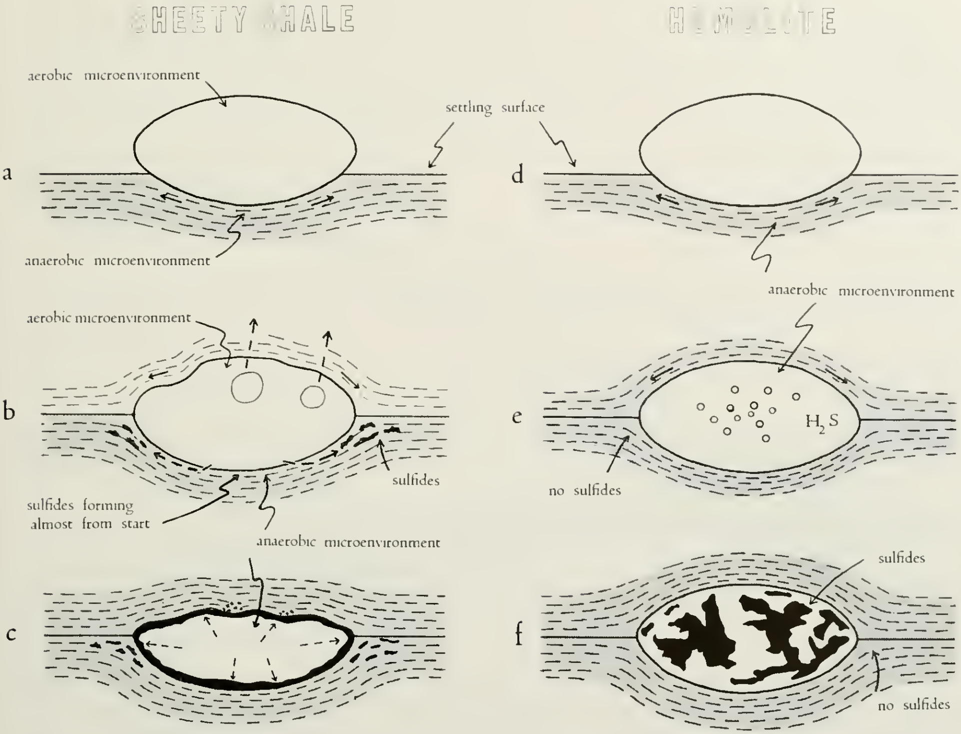
SHEETY SHALE
HUMULITE
aerobic microenvironment
settling surface
a
d
anaerobic microenvironment
anaerobic microenvironment
aerobic microenvironment
b
e
sulfides
H_2S
no sulfides
sulfides forming almost from start
anaerobic microenvironment
sulfides
c
f
no sulfides

FIG. 35. Bacterial decomposition and subsequent diagenetic emplacement of sulfides in coprolites from sheety shales (*a–c*) and from humulite (*d–f*). In the sheety shales an aerobic phase of decay affected primarily the upper half of the fecal mass, reducing its volume. In the lower half, anaerobic conditions were established almost immediately; the resulting gases (primarily H_2S) evidently were not vented to the surface, so that sulfides and sulfates accumulated in the periphery of the mass and outside of it. The aerobic environment on the upper surface was replaced by an anaerobic one after deposition of a thin layer of sediment. In the humulite (*d–f*) the microenvironment was anaerobic from the start, resulting in a much smaller loss of volume and in the deposition of sulfides throughout the fecal mass.

aerobic decay in the upper half. This was rapid and resulted in appreciable loss of volume. In the lower half, anaerobic rotting took place almost from the start. Such gas as was released beneath the specimen is now represented by the small sulfide (sphalerite) bodies beneath the settling surface. After deposition of a blanket of mud the aerobic process became anaerobic. This is indicated by the fact that the mass is not entirely reduced and also by the presence of small sulfide bodies in the shale immediately above the specimen (fig. 35, *a–c*).

In the humulite the burial environment evidently was so severely toxic that anaerobic conditions prevailed from the first (fig. 35, *d–f*).

How much sediment is required to bring about an anaerobic environment around a carcass or other decaying mass and to be sufficiently strong to hold the parts in place? Little information is at hand at this time. In connection with the problem of gas release during decomposition, Hecht (1933) reports that a layer of sediment 4–7 mm. thick prevented fish carcasses from floating off the bottom. The thickness of sediment cover depends,

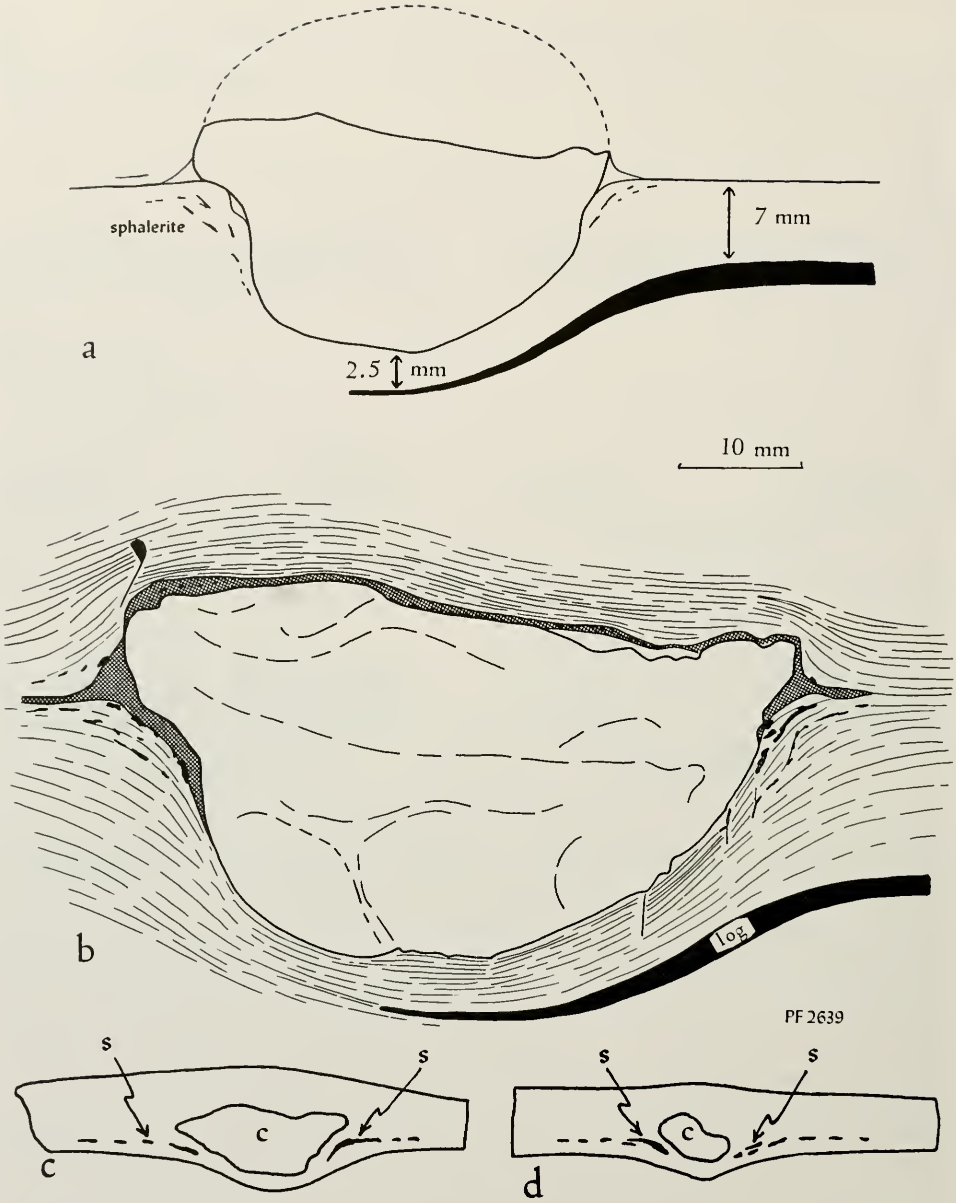

FIG. 36. Vertical sections through coprolites. (*a*) Upper surface of coprolite, PF 2639, typically flattened as a result of aerobic decomposition. Sphalerite crystals are located beneath settling surface, around edge of coprolite. The edge of a driftwood stem, already flattened before deposition of the coprolite, was bent as the weight above it depressed the settling surface. (*b*) The same specimen, showing above and on the sides a thin, dense, deep black layer of shale mixed with decomposed fecal material; note its extension along the settling surface. Small normal faults in the shale beneath and above the specimen are associated with sphalerite (see also pl. 47, B, for internal structure of this coprolite). (*c* and *d*) Sketches, natural size, showing relation of sphalerite (s) to coprolites (c) from Logan Quarry (see pp. 100 sqq.; *c* is specimen CM-2; *d* is specimen CM-3).

no doubt, on a variety of factors, such as the nature and density of the mud, the temperature, the water movements, the relative aeration and the depth of water, the size of the carcass and its condition when it reached bottom. For this reason it is not possible to determine generally applicable values. Estimates have to take into account the sum total of the evidence available in a specific situation. Under favorable circumstances such as existed during deposition of the Mecca Quarry shale this factor can, however, be determined quite accurately (see below, p. 170).

2. *Application of the Method to the Mecca Quarry Shale*

Application of the above discussed method for the determination of the rate of deposition in terms of absolute time to the Mecca Quarry shale requires specific information relating to the following topics:

The density of occurrence of vertebrate remains throughout the profile, the causes of death of the animals, and the fate of the carcasses prior to burial.

The speed of aerobic bacterial decomposition of similar animals under modern, natural conditions in an environment which is at least locally comparable to the depositional environment of the Mecca Quarry shale.

The amount of mud that accumulated on the carcasses from the time they reached bottom to the stage when the bones were no longer held in place by soft parts.

(a) DENSITY AND NATURE OF FOSSIL CONTENT

The evidence concerning this point is discussed elsewhere and needs to be but briefly summarized below.

The density of occurrence of fossil vertebrates in the black sheety shales in Parke County has been discussed on pages 153–155; for the present purposes it may be recalled that the accumulation is greatest in the black levels, and greater at the site of the Mecca Quarry than at the Logan Quarry. Mecca Quarry (about 20 m^2 by 31 cm. thick) contained about 304 individuals; Logan Quarry (about 200 m^2 by 48 cm. thick) contained about 462 individuals (see p. 190 for details of calculation of these figures). Not a single specimen was recovered that may reasonably be assumed to have died due to causes other than predation, except possibly the very large shark (PF 2201, pl. 24, B) at Logan Quarry. All other specimens (p. 136) show signs of major or minor mutilation or may be described as having been eaten and subsequently disgorged (stomach residues). Of importance to the present topic is the fact that the vertebrates of the Mecca Quarry shale reached the bottom mud in injured or partly digested condition, so that they were for the most part in an already precarious state of articulation prior to burial and bacterial degradation (p. 131). In specimens from Logan Quarry, this applies to the vicinity of wounds.

(b) SPEED OF AEROBIC BACTERIAL DECOMPOSITION

At the present there are no figures in the literature concerning the speed of aerobic bacterial decomposition of fishes under circumstances similar to those that probably existed in the Mecca environment. The choice of site and time of appropriate experiments was guided primarily by three considerations: the generally accepted view that the climate of the Pennsylvanian was warm and humid; the probability that the Mecca Quarry shale, at the time of its deposition, resembled fairly closely the black muds that are currently accumulating in many situations along the Gulf coastal plain of North America; and finally, the availability of laboratory facilities within easy reach of the field stations.

These conditions coincided in southern Louisiana in the general vicinity of New Orleans, in the summer of 1956 (see description of the area, p. 114), where we were graciously offered the use of the biological laboratories of Tulane University and a suitable boat with outboard motor and trailer as well as much needed information concerning the location of appropriate sites for the experiments (fig. 26). The experimental sites chosen were quiet swamp bayous where the water current is slow (as in Bayou Labranche) or virtually absent (as in Sarpi Bayou); a small, fairly deep swamp pond with reducing conditions at the bottom east of Sarpi Bayou; a nearby shallow cattail marsh; a semi-stagnant ditch near well 7, west of Sarpi Bayou, entirely covered with a floating mat of water hyacinth and alligator weed (see pl. 14, A); and a tidal lagoon, Chicot Lagoon, near Chef Menteur, east of Lake Pontchartrain.

For the experiments, predator-proof, fine-mesh wire cages were built (see p. 20). Fresh dead fishes were placed in these cages and the latter were submerged at the chosen sites. The weight of the cages caused them to sink slightly into the loose surface sediment. The cages were secured by means of ropes to nearby trees or to buoys. Microscopic animals could have entered the cages and might have contributed to the degradation of the experimental animals, but it seems extremely doubtful that this would have made any significant difference in the length of time it took to disarticulate the fishes. It is also possible that the bacterial decomposition products would have poisoned animal scavengers. The data recorded in the course of these experiments are compiled in Table 9. The pH of the water was found to be close to neutral. The salinity ranged from virtually fresh water to slightly saline at Chicot Lagoon. Of significance are the high water temperatures, 24° to 37° C. There is no evidence that anaerobic conditions developed in any of the sites; decomposition was primarily aerobic. Unfortunately, we did not establish the minimum time required for the disarticulation of the specimens because we assumed that the process would require at least two weeks. At the insistence of our colleagues at Tulane University, who had a better idea of decomposition rates in that area during summer, we did check the cage in Chicot Lagoon after 6½ days and discovered that the degradation process had entirely reduced the soft parts of the fish and that the bones were entirely disarticulated. All other sites were then visited as soon as possible, and the same findings prevailed in all instances. In one case (Station 3), a small amount of bad-smelling whitish material was present with the disarticulated bones. This is of great interest, because the black smelly mud in which the experimental fish was permitted to decompose unquestionably indicated the presence of reducing conditions. Since this observation is in conflict with the experiments of Hecht (1933) we must assume that some oxygen was present in the bottom mud of the little pond at Station 3, and that aerobic decay is possible even in situations where the oxygen content is extremely low.

There would seem to be no doubt that under the conditions set forth, the speed of bacterial decomposition is very great indeed, evidently less than one week for a fish weighing 12 ounces. Of notable interest is the fact that the different local environments in which the fishes were permitted to decay seem to have had no significant effect upon the speed and completeness of the degradation process. Everything indicates that the conditions under which the decomposition process takes place most efficiently are not critical at all, except for the temperature.

(c) SEDIMENT ACCUMULATION OVER CARCASSES

A clue as to the thickness of the sediment cover that accumulated over the carcasses during the decomposition process in the Mecca Quarry shale environment may be found

TABLE 9.—EXPERIMENTS IN FISH DECOMPOSITION IN LOUISIANA, 1956

			INITIATION			TERMINATION			
Cage number	Station name and number	Subject of experiment; length and weight	Date and time	Depth of water	Temperature of water	Date and time	Depth of water	Temperature of water	Duration of experiment in days
1	1, Sarpi Bayou	Catfish (32 cm., ca. ¾ lb.)	July 9, PM	16–20 in.	24.5°C.	July 21, AM	1½ ft.	26.5°C.	11½
2	2, Sarpi cat-tail swamp	Catfish (32 cm., ca. ¾ lb.)	July 10, AM	8 in.	25.5°C.	July 21, AM	partly exposed	—	11
3	3, Sarpi pond	Catfish (32 cm., ca. ¾ lb.)	July 10, AM	4 ft.	—	July 21, AM	4–5 ft.	—	11
4	4, Sarpi, near Well 7	Catfish (32 cm., ca. ¾ lb.)	July 10, AM	3 ft.	—	July 20, PM	2 ft.	—	10½
5	4, Sarpi, near Well 7	Shrimp, 6 in.	July 10, AM	3 ft.	—	July 20, PM	2 ft.	—	10½
6	5, Bayou Labranche	Catfish (32 cm., ca. ¾ lb.)	July 11, AM	ca. 2 ft.	26°C.	July 18, AM	2 ft.	28°C.	7
7	6, Bayou Trépagnier	Catfish (32 cm., ca. ¾ lb.)	July 11, PM	ca. 1 ft.	34.5°C.		cage lost		
8	7, Chicot Lagoon	*Chaenobrythus* (ca. 7 in.; ca. ½ lb.)	July 13, PM	1 ft. (low tide?)	37.2°C.	July 20, AM	2 ft. (high tide)	31°C.	6½

in sections through specimens at right angles to the bedding planes. Examination of such sections by reflected light shows the shale to be finely striated parallel with the bedding planes. In view of the microscopic structure and the flaky nature of the microscopic components of the shale (see p. 105) there would appear to be no doubt but that the fine striation represents microbedding of the shale materials. On both the upper and the lower sides of the specimens this microbedding follows the surface irregularities of the specimens. On the whole, the upper sides of the specimens are less regular than the lower sides, and this irregularity is reflected in the more wavy microbedding of the shale (pl. 50, C). Gases produced during decomposition of the carcasses were released along the upper surface of the specimens. The release of gas bubbles tended to disrupt the orderly arrangement of the scales of the fishes and to render the upper surfaces of the specimens notably uneven. The mud particles that accumulated above the specimens were thus repeatedly disturbed and realigned while those below the specimens remained relatively undisturbed.[1] If the microbedding is followed upward from the upper surface of the specimens, it may be noted that the wavy pattern disappears some distance above the specimen surface. There the bedding is essentially regular and merely follows the overall relief of the specimen, but not the irregularities of the specimen surface. The history of the decomposition process from the time of the arrival of the specimen at its burial site to the time of its reduction to a vertically narrow band of skeletal parts is thus reflected in the disturbance of the mud column that had meantime accumulated above it. The disturbed, wavy band of shale thus represents the column of mud that had accumulated during the mentioned interval. In all the specimens from the Mecca Quarry where this was checked this layer of disturbed shale is close to 1 mm. thick on the average. In specimens from the Logan Quarry it is about 2 mm. thick.

It may here be objected that this explanation ignores compaction of the shale entirely. The question of compaction of the Mecca Quarry shale is discussed on page 176. We have good reason to believe that the Mecca Quarry shale suffered very little compaction beyond water loss, and there is evidence to suggest that the mud accumulating above the specimens had already lost most of its interstitial water and was a fairly dense, sticky muck.

On plate 49 a pellet of gastric residue from Logan Quarry containing palaeoniscoid and acanthodian scales and much groundmass resembling fecal material is shown in vertical section by reflected light. Near the middle of its upper surface and near the right end there are palaeoniscoid scales protruding into the shale above. The palaeoniscoid scales inside the center area of the gastric pellet show funnel-shaped arrangement pointing toward the protruding scale. Inside the funnel opening there are mostly acanthodian scales. The events that led to this remarkable picture are not difficult to reconstruct (see fig. 37); the gastric mass settled into its burial site and began to decompose. In the meantime mud settled over it. Toward the end of its aerobic decay a large gas bubble formed in its central area, aligning the palaeoniscoid scales around it. Then the bubble escaped, piercing the mud on top of the gastric mass and sucking a palaeoniscoid scale and a bit of groundmass with it up into the escape canal in the mud. Inside the fecal mass the palaeoniscoid scales were pushed into a funnel-shaped arrangement by a plug of groundmass and acanthodian scales that were sucked into the void left by the escaping bubble. As the bubble escaped through the mud it bent the packed mud particles upward all around the escape duct, and as the

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[1] Occasionally, evidence of gas release may be found on the under side of the specimens also, particularly in thick coprolites (pl. 50, A) and rarely in thin stomach ejects, but here the disturbance along the under side may be due to big bubbles that formed inside the specimen and pushed scales into the underlying mud.

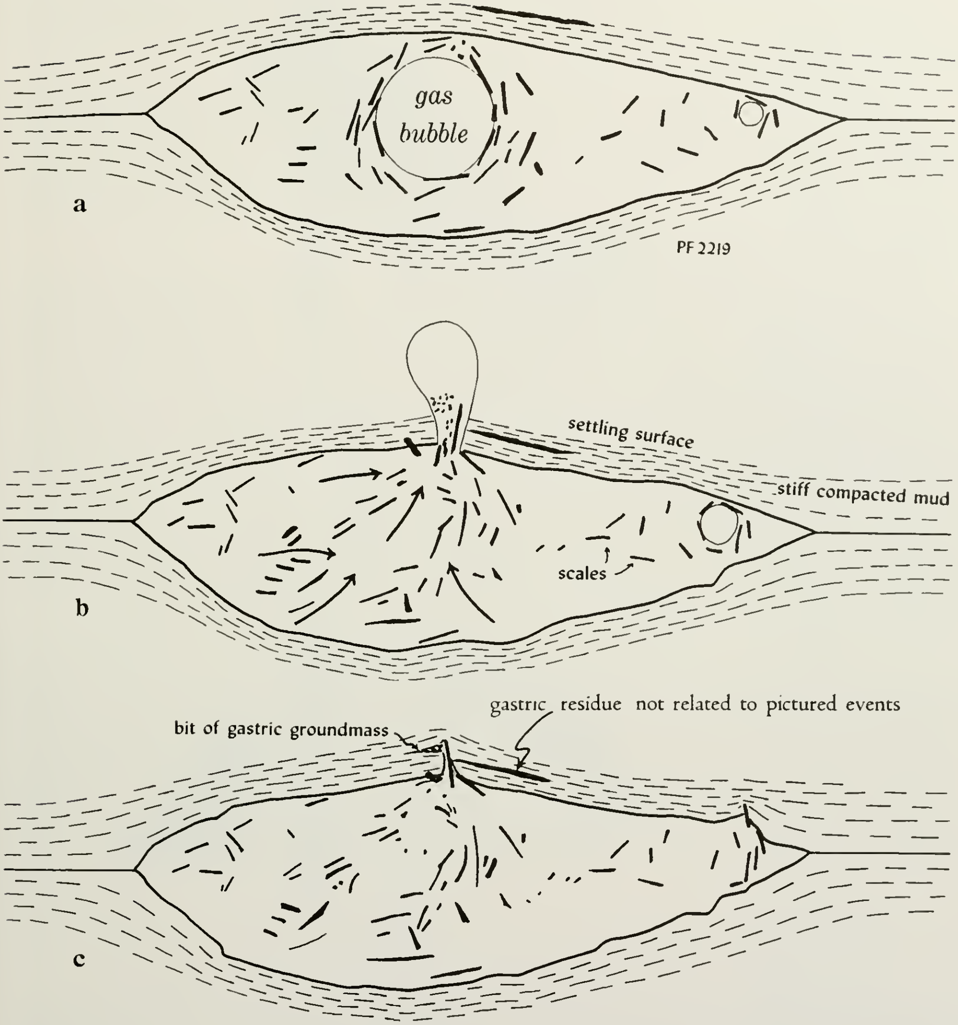
gas
bubble
a
PF 2219
settling surface
stiff compacted mud
scales
b
gastric residue not related to pictured events
bit of gastric groundmass
c

FIG. 37. Vertical section through the gastric residue pictured in plate 49. A final gas bubble formed during aerobic decay (*a*) caused the aligning of the palaeoniscoid scales (black bars). When this bubble was vented to the surface (*b*), 2 mm. of mud had covered the mass. A palaeoniscoid scale was caught vertically in the vent and a small amount of gastric groundmass was draped over the accumulated mud (*c*).

mud settled back it held the expelled palaeoniscoid scale in nearly vertical position. The small amount of gastric groundmass that was ejected with the scale settled horizontally on the left side near the upper end of the ejected scale. Evidence of all these minute details has been preserved in the specimen figured on plate 49. If the layer of mud that covered the gastric pellet at the time when the gas bubble was released had not been thick enough and had not been dense and fairly firm, the scale would have settled horizontally on the pellet. If there had been a notable amount of compaction (aside from water loss) the scale would have been either badly deformed or crushed into more or less horizontal position. The small "flag" of gastric groundmass at the tip of the ejected scale (see fig. 37, *c*) would have been crushed onto the surface of the pellet.

Evidence of gas release with attendant ejection of scales into the mud covering the carcasses was seen in a number of sectioned specimens: PF 2217 (LQ[1]: J); PF 2634 (LQ: J); PF 2635 (LQ: J); PF 3018 (MQ: B2.3, pl. 50, *c*); PF 3019 (MQ: B3.4); PF 3020 (MQ: A2.2); PF 2704 (MQ: A1.4, pl. 50, *b*), and the principal features are the same as those described in the gastric pellet above. Serial sectioning of entire specimens would no doubt reveal the overall gas release pattern of carcasses and gastric residues.

While the gas release phenomena (see also p. 178) dramatically attest to the rapid rate of deposition of the Mecca and Logan muds, there is plenty of other evidence that points in the same direction. A very instructive example is provided by the shark skeleton PF 2202 from level G, Logan Quarry (fig. 38). The specimen is essentially a whole skeleton in almost perfectly articulated condition. The dorsal lobe of the tail fin appears to have been bitten off and there is a break in the vertebral column anterior to the position of the dorsal fin. The animal had evidently been mortally wounded, but neither mouthed nor otherwise torn apart. The carcass settled into the burial ground lying on its right side. Anaerobic conditions were established almost immediately beneath the carcass; hence all of the skeleton except for the left pectoral and pelvic fins is preserved perfectly intact. But the left pectoral and pelvic fins extended up beyond the mud and decomposed aerobically, which led to their disarticulation. The loose pieces did not float away, however, as almost surely would have happened had they not been kept in place by the rapidly accumulating sediment.

In summary it may be stated that the gas release activity during decomposition of the carcasses, stomach residues and coprolites produced important evidence as to the nature and thickness of the mud that was deposited on the specimens during the degrading process. The thickness value at the site of the Mecca Quarry is the mud equivalent of about 1 mm. of shale; at Logan Quarry the value is 2 mm. or slightly more. The mud components were densely packed, leaving very little space for interstitial water. There was only a small amount of subsequent water loss and apparently only negligible compaction due to other causes (for example, loading). Diagenetic changes in the shale must have been minimal.

3. *CALCULATIONS OF RATES OF DEPOSITION OF MECCA QUARRY SHALE*

Evidence presented in the three points above (pp. 167–172) is as follows:

(a). Carcasses, stomach residues and coprolites are still essentially in the state of articulation (or association) in which they reached the burial site in the mud. Minor disarrangements are due to the gas release activity during decomposition.

(b). The bacterial decomposition of fishes of about 12-ounce size under circumstances similar to those in the Mecca environment and at temperatures ranging from 25° to 37° C. was found to be complete in less than one week, probably about 5 days.

(c). A cover of mud equivalent to about 1 mm. of shale was deposited on the specimens at the site of Mecca Quarry (about twice that amount at Logan Quarry), from the time they reached the burial site to the end of aerobic gas release activity in the carcasses.

These data permit simple calculation of the days required for the deposition of the Mecca shale profile. Figures based on this rate (1 mm.= 5 days) for the major divisions of

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[1] LQ= Logan Quarry; MQ= Mecca Quarry; J, B3.4, etc.= microstratigraphic levels.

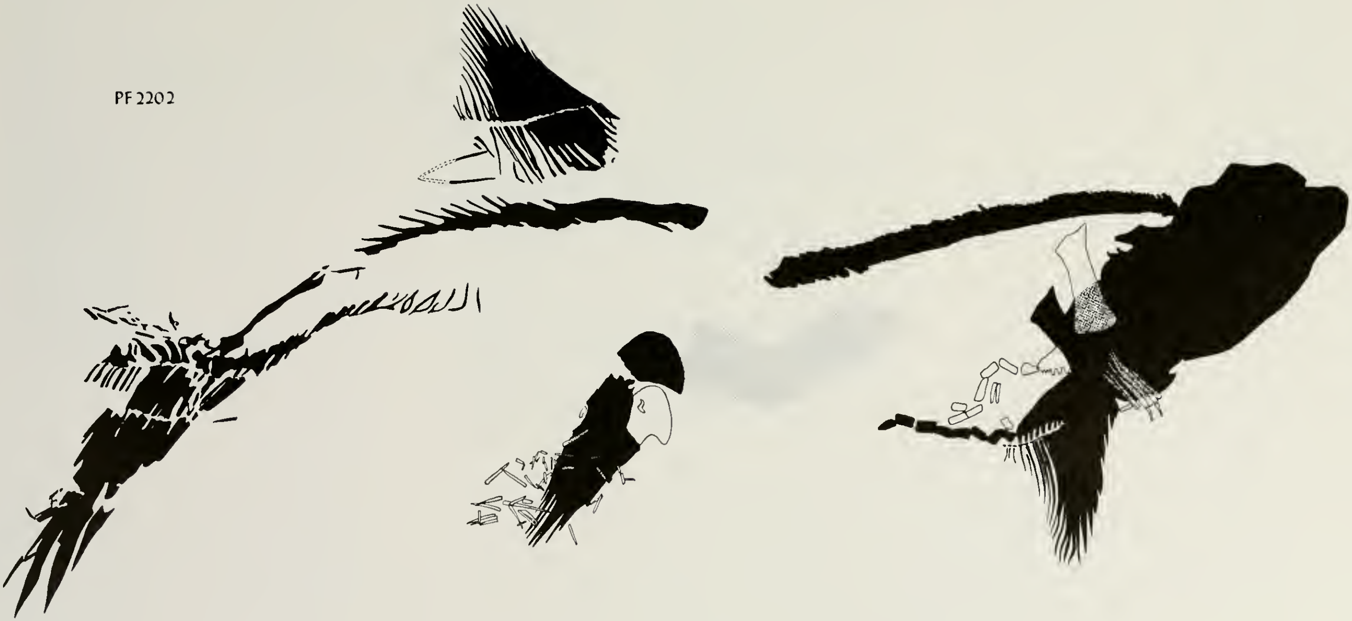


FIG. 38. Skeleton of a 4-foot shark from Logan Quarry shale, level G, Logan Quarry, which lay on its right side on the settling surface. Anaerobic conditions developed rapidly beneath the carcass, so that the elements of the right side, up to the sagittal plane of the body, remained articulated and undisturbed. The left pectoral and pelvic fins, which lay above the settling plane, were attacked aerobically and became disarticulated. The rate of deposition of the sediment was so rapid that the loose fin-rays were not dispersed. Gray area near pelvic girdle represents gastro-intestinal content in place.

the profile are shown on figure 39; the total number of days is 1540, or close to 4¼ years (=1551 days). It must be kept in mind, however, that the determinations concerning sediment cover were based on specimens in black (but not the blackest) shale only; it is very probable that this value varies slightly with the particular characteristics of different grades of black shale, so that the values obtained merely reflect the order of magnitude of the time involved (about 4 years) rather than actually 1540 days.

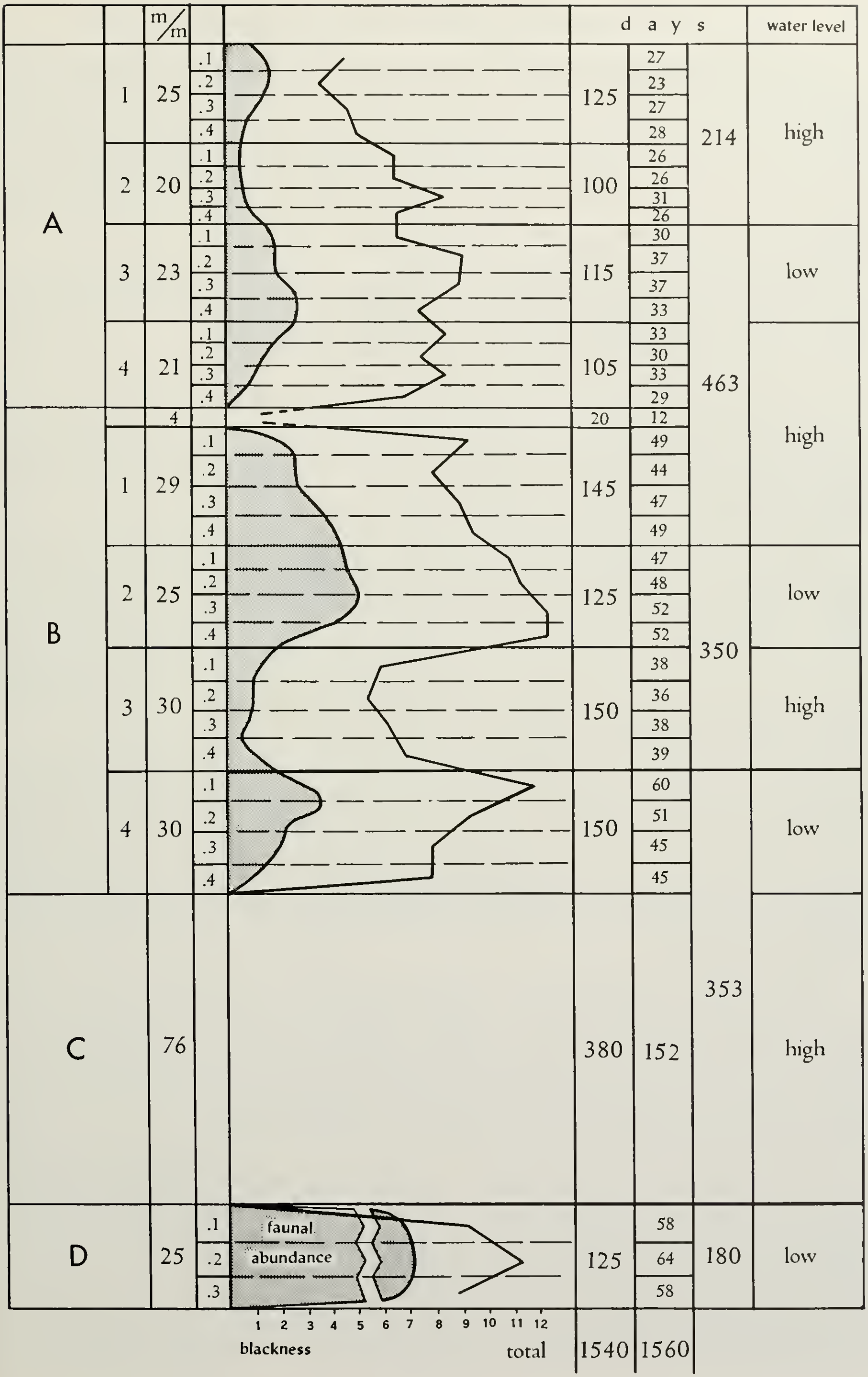
In connection with the fossil content (fig. 32), the reflectivity of the shale (fig. 5) and the microscopic components of the Mecca Quarry shale (fig. 25) it was noted that there is an unmistakable periodicity in the Mecca Quarry shale that might be summarized as follows: four black levels with colored microscopic components and high concentration of fossil content alternate with four gray levels lacking colored components and with low concentration of fossils. In view of the above time value of about 4 years for the whole sequence, there would appear to be little doubt but that each pair of gray and black levels represents the sediment accumulation of one year.

The values obtained on the basis of 1 mm.=5 days assume that gray and black shale accumulated at the same rate, which is highly improbable. The gray levels, containing a large amount of clay, very probably accumulated faster than did the black layers, which consist largely of organic degradation products. The presence of colored plant decomposition products in the black, and absence of such in the gray levels suggest strongly that the water was well aerated during gray mud deposition, poorly aerated and nearly stagnant during the periods when black muck was laid down. These conditions no doubt had an effect upon the microenvironment of the decaying carcasses. The calculations of rate within the Mecca Quarry shale profile should thus be adjusted, since a greater thickness of gray mud accumulated over a carcass during its aerobic decomposition phase and the accumulation of 1 mm. of black muck required a little longer than 5 days.

For the sake of simplicity it was assumed that the value 1 mm.=5 days is applicable to shale of medium blackness. Grayer shale would require less time for the accumulation of 1 mm.; blacker shale would require more time. The gray scale measurements (see p. 17) were used for this purpose according to the following schedule:

Reflectivity grade	Time (days) for 1 mm. of deposition
0	2
1	2.5
2	3
3	3.5
4	4
5	4.5
6	5
7	5.5
8	6
9	6.5
10	7
11	7.5
12	8

FIG. 39. Profile of Mecca Quarry shale at Mecca Quarry, showing thickness of microstratigraphic units, vertical distribution of fossil content (gray tone), relative blackness of shale levels, and calculations of rate of deposition of shale, as discussed in the text. Successive black and gray levels are interpreted as representing periods of low and high water respectively.



		m/m		days			water level
A	1	25	.1	125	27	214	high
			.2		23		
			.3		27		
			.4		28		
	2	20	.1	100	26		
			.2		26		
			.3		31		
			.4		26		
	3	23	.1	115	30	463	low
			.2		37		
			.3		37		
			.4		33		
	4	21	.1	105	33		high
			.2		30		
			.3		33		
			.4		29		
		4		20	12		
B	1	29	.1	145	49		
			.2		44		
			.3		47		
			.4		49		
	2	25	.1	125	47	350	low
			.2		48		
			.3		52		
			.4		52		
	3	30	.1	150	38		high
			.2		36		
			.3		38		
			.4		39		
	4	30	.1	150	60	353	low
			.2		51		
			.3		45		
			.4		45		
C		76		380	152		high
D		25	.1	125	58	180	low
			.2		64		
			.3		58		
			total	1540	1560		

The resulting values for all levels are entered in figure 39 as well as the totals for adjacent gray and black levels: A3 to B1, 463 days; B2 and B3, 350 days; B4 and C, 353 days; A1 and A2 plus D, 394 days. The number of days for the whole sequence comes out at 1560, nearly the same as in the other calculation (1 mm.= 5 days)—an average of very close to 5 days per millimeter of shale. If the above figures for yearly cycles seem astonishingly close, it should be noted that even more accurate results are potentially possible, namely, by measuring the thickness of sediment cover that accumulated over the specimens during aerobic decomposition at all levels of the profile.

The evidence here presented strongly suggests that the cycles of deposition of gray and black shale reflect seasonal changes between relatively wet periods and relatively dry periods: a yearly pattern widespread at the present in subtropical climates.

I. COMPACTION OF THE MECCA AND LOGAN QUARRY SHALES

The question of compaction of sediments was recently reviewed by Weller (1959 and 1960). The processes that lead to lithification of a sediment are still rather poorly understood in detail, and the expression of compaction (the reduction of the interstitial pore space) in quantitative terms meets with serious difficulties.

Measurements of natural fine-grained marine clays show initial porosities of 80 per cent or more. Compaction results in the gradual elimination of the interstitial water and the tight packing of the sedimentary particles due to pressure exerted by accumulating overburden. This process is thought to be accomplished in several stages. The first of these stages involves interstitial water loss to a point where sedimentary particles come into contact with each other but suffer little rearrangement. The porosity at this point is about 45 per cent in common muddy sediments, which corresponds to the average plastic limit of many sediments that have been tested.

The next stage involves the rearrangement of particles, which results in closer packing. The porosity is reduced to about 37 per cent. Further compaction is brought about by the distortion of the mineral grains. The harder, more resistant particles come into contact with each other and the softer clay minerals are thought to be squeezed into the interstices between the harder grains. The porosity may be reduced to 10 per cent and the original volume may be reduced by 78 per cent. Deformation or crushing of the harder particles may lead to loss of porosity and the fully compacted sediment may occupy only 20 per cent of its original volume.

These estimates are applicable to ordinary fine-grained marine muds (but see limitations as discussed by Weller, 1959). Organic sediments present somewhat different problems, as was correctly pointed out by Weller. Reduction in volume is brought about by the degradation of the organic substance and by compaction due to the elimination of pore space, so that one might expect sediments of high organic content to suffer even greater loss of volume than was estimated for ordinary fine-grained muds.

Our own evidence tends to suggest, however, that the processes leading to lithification of predominantly organic muds may differ radically from those that apply to ordinary muds. There is evidence in the Mecca and Logan Quarry shales that water loss and thus drastic reduction in porosity take place very rapidly, and that the limit of plasticity of such sediments may lie at a far lower level of porosity than in ordinary muds.

Our evidence is considered below under the following headings:

1. The nature of modern sediments of high organic content.
2. The shape and nature of microscopic particles in the Mecca and Logan Quarry shales.

3. Lack of distortion due to compression of hollow (air-filled) cavities in bones.
4. Gas release phenomena in decomposing carcasses and gastric residues. Lower versus upper side of specimens.
5. Preservation of logs and sticks.
6. Vertical-to-bedding position of teeth and other skeletal elements of fishes.
7. Snail burrows.

1. *THE NATURE OF MODERN SEDIMENTS OF HIGH ORGANIC CONTENT*

Modern sediments very probably similar to those that produced the Mecca and Logan Quarry shales are found in certain bayous, swamp and marsh ponds along the Gulf Coast of North America. The geographic location of such sites as we visited are described (p. 114). The sediments in these waters differ from the more familiar marine and fresh-water lake deposits in a significant aspect: namely, in the absence of a recognizable bottom or mud surface. Instead, these muds consist of a graded column of mostly organic particles from just beneath the water surface, where the particles are coarse, to a depth of 10 feet or more, where the particles are microscopic and densely packed. Mud of the bottom 2 feet or so tends to adhere to a pole driven to the base of the mud profile, and reducing conditions prevail at that depth, to judge from the smell of the sediment. Above this level the organic particle size increases toward the top and the mud lacks adhesive qualities. Fine-grained clastic particles are interbedded with the plant degradation products.

Muds of this type have not been studied to date, as far as we know. Detailed analysis and the study of carefully collected cores should prove of great interest. The processes leading to lithification of muds of this kind are likely to differ greatly from those of ordinary muds.

The nature of the plant decomposition products (opaque as well as colored flakes, see p. 105), the geographic location of the depositional environment (bottom lands close to the sea), depth of water and mud (shallow) frequently covered by floating mats of vegetation, lack of sessile fauna or infauna—all these characteristics lead to the conclusion that muds of the described character may have been the source material for the Mecca and Logan Quarry shales.

Figure 27, depicting our general idea of the depositional and ecological environments of the Mecca and Logan Quarry shales, is modeled after our observations on bayou muds as described above, but it incorporates such evidence as may be deduced from the mode of preservation of the fossils (see below).

2. *THE SHAPE AND NATURE OF MICROSCOPIC SHALE PARTICLES*

In the discussion of the microscopic structure of the shale (p. 105) it was pointed out that the organic particles (plant decomposition products) are flaky in shape. It was argued that these represent actual (though highly degraded) remains of plants rather than organic coagulates and that they are present as either opaques (micrinite?) or colored particles. This concept conflicts with views expressed by coal petrologists, for example, Stach (1932), as regards the origin of flaky micrinite in coal.

Our evidence lies in the fact that while the organic substance that was reduced to colloidal state entered and stained the hard parts of the enclosed vertebrates (bones, teeth) to various shades of brown, and even jelled within the minute canals of these structures (for example, dentine canals and the like), the large cavities within these denticles, teeth, spines and bones are hollow (often actually filled with air), evidently because the flaky nature of the surrounding sediment blocked the entrance pores and canals of these elements.

This may readily be seen on sections such as the one depicted on plate 52 showing a *Petrodus* skin denticle in side position with regard to the bedding plane. The straight edge of the denticle, on the right side of the picture, is the base of the denticle which adhered to the skin of the shark in life. Pores leading to the interior canal system of the denticle are distributed over the base surface of these denticles. Two such pores are visible near the lower end of the denticle base and enlargements of these areas show clearly that micrinite flakes blocked these entrance pores so effectively that none of the clay minerals could enter the cavities and fill them as happens in ordinary sediments. Colloidal material, however, did enter the denticle, stained its substance, and jelled within the dentine canals and along the walls of the large cavities, thus providing them with sharp, dark outlines.

These observations prove beyond doubt that the organic material, as it draped around the potential fossils ("Fossilisants," Hecht, 1933, p. 176), was to a large measure in the form of solid flakes and has remained so in the course of subsequent diagenesis. It is of interest to note that these flakes must have packed down tightly around the future fossils to form a tough fabric capable of withstanding considerable pressure, else they would have been squeezed into the hollow spaces within the vertebrate tissues.

3. *LACK OF DISTORTION DUE TO COMPRESSION OF HOLLOW BONE CAVITIES*

It was mentioned above that the large cavities in teeth and spines are hollow; they were not filled initially by sediment, and often not even secondarily by minerals. This is the rule in all fossils in the Mecca and Logan Quarry shales. Plate 53, A, shows the posterior end of an edestid spine, broken along the bedding plane of the surrounding shale. The substance contains numerous longitudinal canals that are empty. Along the margin of the element (on the left side of the picture) the canals are filled with gypsum, and so is the large canal near the top of the photograph. Plate 53 also shows thin sections of an acanthodian spine (B) and the posterior end of a palaeoniscoid mandible (C). In both examples the internal cavities are empty. In the case of the palaeoniscoid mandible the bone substance surrounding the cavities consists of extremely delicate rods and partitions.

This would indicate that the mud in which these structures were buried could not have been compacted in the same mode as ordinary sediments, else the specimens would have suffered severe internal crushing (see pl. 51, A, and Zangerl, 1948, p. 13, for an example of such crushing). Bones and even calcified cartilage, a very pliable substance, show very little plastic deformation (see below).

Hollow skeletal fragments were also observed embedded in fecal masses. This is rather remarkable since fecal matter is fairly plastic and under ordinary compaction should be expected to have been forced into these vacant spaces.

4. *GAS RELEASE PHENOMENA IN DECOMPOSING CARCASSES*

The vertebrates enclosed in the Mecca and Logan Quarry shales show evidence of both aerobic and anaerobic decomposition and the production and release of decomposition gases. Gas release, especially during the aerobic phase of the degradation process, tends to injure the histological structure of such elements as calcified cartilage, and the injury invariably affects the upper side of the cartilage elements as they lie in the mud. Plate 51 and figure 40 show a section across the articulated fin of a shark. About nine fin-rays lie side by side. Along the lower margins of these fin-rays the calcified cartilage prisms are perfectly aligned as they were in life. On the upper sides they are injured in such a way that small groups of adjacent prisms have fallen into the interior of the fin-rays, which were filled, in life, with uncalcified cartilage tissue. The spaces between the broken cartilage pieces are filled with calcite.[1] Along the lower edge of the fin, in the wedge-shaped spaces between the fin-rays, and on the upper side of the fin, usually near the middle of the fin-rays, there are small, cone-shaped aggregations of sphalerite crystals (pl. 51, C and D) that are more closely spaced near the fossil and separated from each other by shale. These sphalerite accumulations very probably represent the gas bubbles released during the anaerobic phase of the decomposition process when hydrogen sulfide was present in appreciable quantities. At that time, very soon after burial, the thin layer of mud that had accumulated above the specimen was so dense already that it did not permit escape of the gases to the water above. The bubbles were held in place by the sediment and the cavities were subsequently filled by sphalerite.

The described mode of preservation of vertebrate structures as delicate and perishable as are the rays of a shark fin demands a number of conclusions as to the nature of the sediment that enclosed it soon after burial. Anaerobic conditions prevailed beneath the fin virtually from the time it came to rest at its burial site and burial level in the mud column (fig. 27). For this reason the calcified cartilage prisms on the lower side which were connected to each other by connective tissue along the periphery of the fin-rays, remained intact. On the upper side of the specimen conditions were aerobic for a short time. The soft interior of the rays partially decomposed and the escaping gas broke the wall of the upper side (fig. 40). The pieces fell into the interior of the rays. Partially decomposed skin prevented the sediment particles from entering into the central areas of the fin-rays. A rather dense layer of mud formed above the fin, and the slow process of anaerobic degradation began. The gases produced during this stage and later rose some distance into the overlying sediment, but could not pierce it and escape; more bubbles formed underneath them and were held in place by the sediment.

Sediment laid down above the fin was so densely packed from the moment of deposition that little further compaction took place subsequently and under eventual load of overburden. If compaction of the mode described by Weller (1959) for ordinary marine muds had operated in the Mecca and Logan Quarry muds, we should expect the interior of the cartilage rays to have become filled by sediment, traces of the gas release phenomena should be expected to have been destroyed and it would seem inconceivable that the perfect arcs of calcified cartilage prisms on the lower side of the specimen could have survived, under the deforming effects of severe compaction, down to 50 per cent (or even 20 per cent) of the original mud volume (Weller, 1959). We must conclude that the processes of sedimentation and compaction of the Mecca and Logan Quarry muds were of an entirely different nature from those of ordinary muds.

5. *PRESERVATION OF LOGS AND STICKS*

Identifiable plant material is extremely rare in the Mecca and Logan Quarry shales. But logs and stem pieces are common (pl. 20, A, B, D). These are preserved in flattened condition, show longitudinal striation at the surface, and resemble, on section, anthraxylon (vitrain?) bands in coal. The flattened condition of these stems is probably not due to compaction so much as to bacterial decomposition of thin-walled, pithy logs. Had the logs reached the plane of equilibrium in the mud column (fig. 27) in firm, unflattened condition, and had they remained so for a long time, gradually flattening out, one should expect in the fossils buried slightly above them and partially overlapping them, a vertical downward

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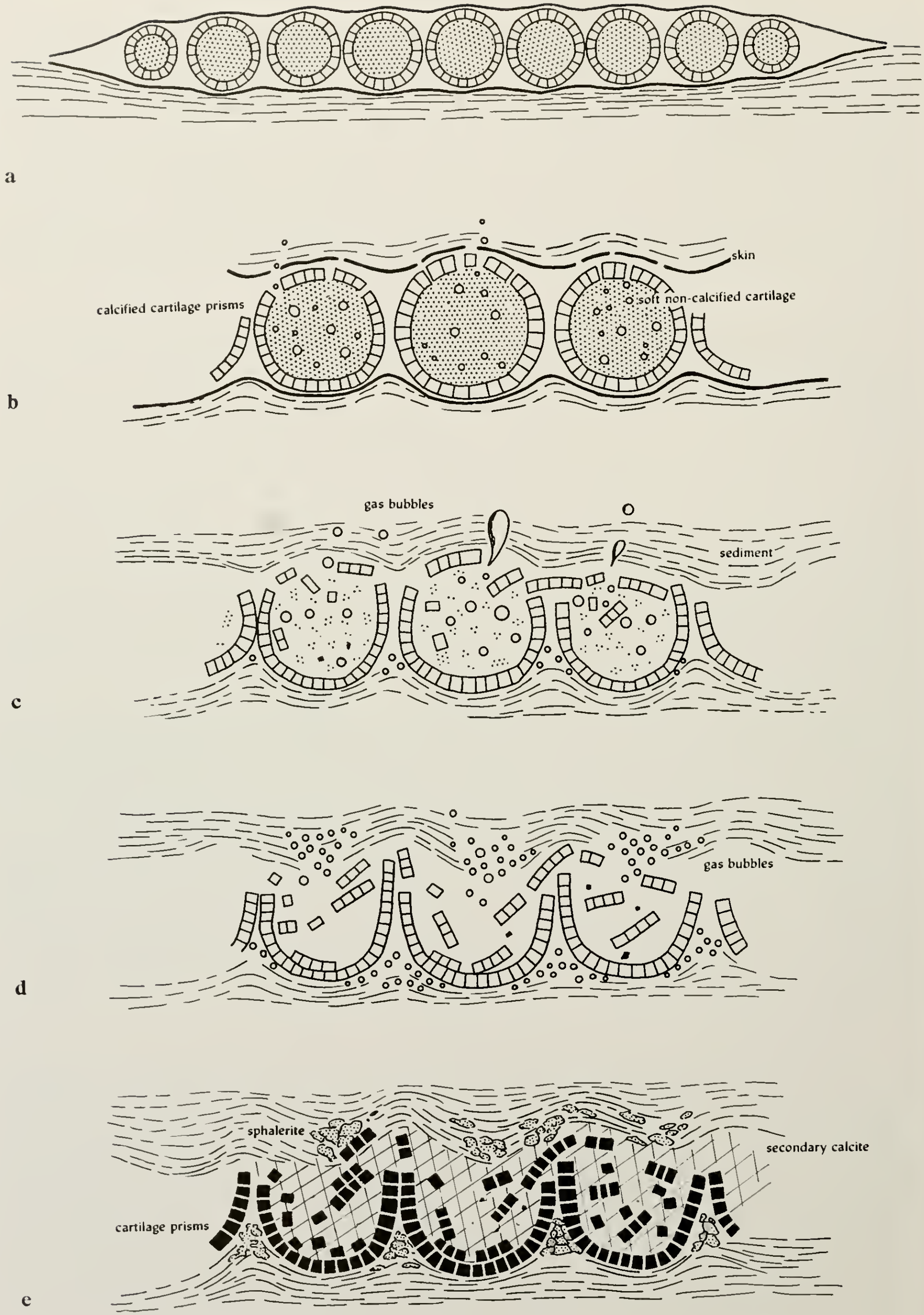
[1] The prisms have been chemically altered (see p. 102), the original carbonate presumably providing a source for the secondary infilling of the interiors of the rays with calcite.


a
skin
calcified cartilage prisms
soft non-calcified cartilage
b
gas bubbles
sediment
c
gas bubbles
d
sphalerite
secondary calcite
cartilage prisms
e

displacement of the parts that overlapped the log. Nothing of this sort was noted. The exact opposite is the case (fig. 36: the log beneath the coprolite was already flattened at the time the coprolite reached the settling plane).

Occasionally stem pieces and other plant parts are preserved as mere surface films. It may be assumed that these tissues had reached an advanced state of degradation by the time they reached the burial site. Nearly intact cattail leaves in highly advanced state of decomposition are sometimes seen among the debris of modern bayou mud.

6. *VERTICAL-TO-BEDDING POSITION OF TEETH AND OTHER SKELETAL ELEMENTS*

Very rarely, isolated skeletal remains of vertebrates are buried in the shale vertical to the bedding planes. An unidentified, minute (440 μ) scale(?) was seen in a thin section (pl. 54, C) of Logan Quarry level M, which is a thin marine shale below the coal. If we are to accept the suggested concepts relative to the compaction of coal, which is thought to be very intense, we should expect the underlying material to have suffered accordingly. Yet in it a minute delicate particle was preserved in upright position without suffering either distortion or breakage.

A moderately large shark tooth in the Mecca Quarry shale, level B4 (pl. 54, A and B), likewise was buried and preserved in upright position. A joint had formed in the plane of the tooth, which accounts for a certain amount of injury to the specimen. The tooth shows no evidence of distortion due to compression, but it does show a system of fine cracks in the brittle outer tooth substance (vitrodentine) that displays an arrangement similar to what might be expected if a stress coat had been applied and it had been subjected to vertical pressure. On the tooth mold, across the joint, the crack pattern is visible, though not nearly as sharply defined. This would indicate that the crack pattern was either present before the tooth was buried or developed after burial prior to the time when the enclosing mud had lost its plasticity. Since none of the modern and Tertiary shark teeth that we have seen show a similar crack pattern of the vitrodentine, the latter possibility would seem more likely.

7. *SNAIL BURROWS*

Snail burrows are very rare in the sheety Mecca Quarry shale proper, but they are common in the black bedded shale immediately above it (see p. 28). Within the shale at Mecca Quarry, near the top (portion "A" of the quarry profile), two burrows extend through the shale at an acute angle and are readily distinguishable from the surrounding shale by the different color and fine texture of fecal material, most coarse-grained along the middle of the bottom (pl. 20, C). In the present condition the burrows are flattened to a lenticular cross section about 5 mm. thick (at a maximum) in the middle and about 20 mm. wide.

FIG. 40. Cross section of shark fin illustrated on plate 51. The illustrations follow our interpretation of the events that led to the present condition of the specimen. (*a*) Fin-rays, consisting of peripheral calcified cartilage and held together by soft tissues and skin, have arrived on settling surface. (*b*) Aerobic decomposition attacks the skin, the connective tissue and the soft uncalcified cartilage, with release of gas bubbles. (*c*) Final stage of aerobic decay; broken pieces of calcified cartilage settle into interior of fin-rays. (*d*) A layer of mud has covered the fin, stopping the aerobic action; anaerobic rotting has begun, producing no further change of form, and gas bubbles are retained in the sediment; the flaky sediment is too coherent to settle into the interior of the fin-rays. (*e*) Diagenetic infilling of the interior of the fin-rays with calcite, possibly derived from cartilage prisms; sulfate crystals above and between fin-rays mark the position of former gas bubbles.

We may assume that the snail, as it burrowed through the sediment, left behind it a more or less circular, water-filled tube and a fecal trail. Some amount of loose sediment from above may also have settled into the tube. Most of the burrows that we have examined contain no snails; in one of them there is a snail but not at the deep end of the burrow. Evidently most of the snails withdrew, leaving a tube partially filled with fecal material and mud. Since some fecal matter is found all through the mud fill of the burrows, we must conclude that the tubes did not get filled with mud from the opening on top. The tubes apparently collapsed and their contents were later flattened out by mild compaction of the sediment. The present thickness of the burrow fills, however, does not serve as an indicator of the amount of compaction suffered by the shale.

8. *SUMMARY ON COMPACTION*

In summary it may be said that the structure of the Mecca and Logan Quarry shales and the nature of the preservation of their fossil content furnish very strong evidence to the effect that the mode of sedimentation and compaction of the highly carbonaceous muds that produced these shales differed radically from that currently thought to apply to ordinary fine-grained marine muds. All the evidence indicates that the Mecca and Logan Quarry muds became nearly compacted at the time of their deposition and that they suffered very little further compaction under loading. The volume reduction of these muds may well have exceeded 80 per cent (for average black levels) but the compaction was effected virtually at the time of deposition at a level in the graded mud column which we may call the settling surface (see fig. 27).

The end stages of the compaction process as set forth by Weller for ordinary muds involve crushing of the harder, more pressure-resistant minerals. If the Mecca and Logan Quarry shales had been subjected to pressures of the magnitude required to bring about such mineral deformation, we should most certainly expect the fossils to have suffered a similar fate. In the total absence of evidence of this sort we may conclude that these shales were never covered by thick blankets of sediment and thus were never subjected to very severe loading.

Some of our conclusions, we realize, radically contradict current concepts of deposition and compaction of predominantly carbonaceous rocks. The evidence presented does not, of course, suggest the reasons why sediments of this type appear to behave differently from ordinary marine muds. Sedimentological work in this area seems definitely indicated.

J. THE ANIMAL COMMUNITIES OF THE MECCA AND LOGAN QUARRY SHALES

1. *INTRODUCTION*

It has long been recognized by paleontologists that the fossil assemblages in any given occurrence, while somehow derived from one or more biological communities, actually represent the preserved remains of burial communities (thanatocoenoses, E. Wasmund, 1926). The interactions of a great many physical, chemical and biological factors determine the overall character of a thanatocoenosis (see Müller, 1951 and 1957, for a general review of these problems). For these reasons the erkenntnistheoretic value of thanatocoenoses varies within wide limits. Under the most favorable circumstances we may expect a burial community to have been derived from the bio-community that existed in and above the burial ground (autochthonous thanatocoenosis), but even so it is never either qualitatively or quantitatively a true reflection of the ancient biocoenosis. Attempts at reconstruction of ancient biocoenoses are destined (even potentially) to remain approximations.

While the outlook in this direction appears rather gloomy, it must be pointed out that in some rare instances a surprisingly high order of approximation may be achieved. The Mecca fauna offers such an opportunity.

As will be shown, the ecological circumstances that prevailed during the short time spans represented by the Mecca and Logan Quarry shales can by no stretch of the imagination be regarded as "normal" organism-environment relationships in balanced ecosystems. It may be argued that this detracts from the general usefulness of the examples, since it renders impossible any comparison with more or less balanced modern ecosystems. We feel that this is, indeed, a valid assertion, except in its implication that many other fossil assemblages do reflect balanced systems. There remains a good deal of doubt that fossil assemblages—formed, as most of them are, in local environments of rapid deposition—ever truly represent balanced conditions. We must face up to the fact that by its very nature, the paleontological record samples principally periods and environments of change rather than of relative stability. Viewed in this perspective, the Mecca and Logan situations are striking examples of ecological unbalance in areas and during the critical times when established environments (coal forests) were destroyed and other environments were being established in their place.

2. *BURIAL COMMUNITIES OF MECCA QUARRY SHALE*

A number of different burial communities may be distinguished in succeeding levels of the Mecca Quarry shale at Mecca Quarry and other geographic locations.

(a) THE CHANNEL CLOD AND THE TRANSGRESSION SHELL BRECCIA

The burial community of the channel clod (stratigraphic discussion, p. 94) consists of countless individuals of the productid brachiopod *Desmoinesia muricatina* which, at West Montezuma, were observed to form accumulations up to two feet in thickness. Many shells of this animal are whole and the delicate shell spines are preserved in interlocking position (pl. 23, A). There are far fewer individuals of the cone coral *Lophophyllidium proliferum*, other brachiopods, a trilobite, crinoids, molluscs, and bryozoans. The burial community thus consists primarily of sessile benthonic organisms. The enclosing sediment is a flaky, soft, dark gray to black clod that readily separates from the fossils.

The unusually fine preservation of the minute, exceedingly brittle brachiopod shell spines (in very friable sediment) indicates beyond doubt that the occurrence represents nearly an autochthonous thanatocoenosis of organisms that lived *in situ* close to the site of deposition for a notable period of time (fossil bioherm). Since the oxygen requirements of such a community could scarcely be satisfied in a depositional environment of large quantities of decomposing organic material (as indicated by the enclosing sediment) we must assume that the community lived and grew in relatively clear, aerated water and that its further development was terminated by its introduction into black muck which then settled all through the crevices of the shell bank (see p. 32).

The channel clod at localities farther east contains the same burial community as at West Montezuma, but the shell material is more broken and does not occur in aggregations such as have been observed at West Montezuma. Here the burial community is entirely allochthonous in character, though very probably derived from situations similar to those near West Montezuma. The transgression shell breccia (see p. 26) is essentially a broken shell accumulation draped immediately over the coal surface. Unquestionably it is an allochthonous aggregation containing the elements present in the channel clod. For the most part this shell debris is reduced to unidentifiable state and is often barely recognizable. It seems likely that the transgression shell breccia was derived in part from the debris contained in the channel muds, with an admixture of shell material that may have accumulated in more open waters to the west. It was deposited on the peat surface in the course of the first thrust of the marine inundation across the coal forest.

Deposits and fossil animal communities comparable to those of the channel clod are absent in the outcrop belt of the Logan Quarry shale of the area under study, but deposits with the general characteristics of the transgression shell breccia do occur. At the site of Logan Quarry the content of shell debris is much sparser than at Mecca Quarry and a whole, well-preserved (pyritized) cephalopod shell was collected from it (top half of level L).

(b) THE BURIAL COMMUNITY OF LEVEL D, MECCA QUARRY SHALE

The transgression shell breccia of the Mecca Quarry shale is overlain by dense, black, fairly even-bedded sheety shale, designated as level D. The burial community of level D consists of countless individuals of the pectinoid *Dunbarella,* a very few orbiculoid and linguloid brachiopods, fairly abundant conodonts, a fair quantity of young individuals of *Pseudorthoceras,* and some coiled cephalopods. In addition to these invertebrates there are the typical Mecca fauna vertebrates: *Petrodus, Listracanthus,* sharks, palaeoniscoids, "placoderms" and acanthodians. None of the sessile benthos of the channel clod is represented. The entire burial community consists of mobile epifaunal elements.

The undisturbed nature of the shale (p. 160; pl. 8, D and E) and the fragmentation and disarticulation of the remains support the conclusion that the assemblage is of autochthonous character. All of the faunal elements in this burial community are either marine or brackish water animals.

(c) THE BURIAL COMMUNITY OF LEVELS C TO A, MECCA QUARRY SHALE

The burial community of these sheety, gray to black shales is the typical "Mecca fauna," dominated by vertebrates: possibly as many as twelve genera of sharks, palaeoniscoids (perhaps two or more very similar species), two very interesting primitive vertebrates (as yet unstudied) which, for the present purposes, will simply be referred to as "placoderms," and a species of acanthodian probably belonging to the genus *Acanthodes.* The invertebrate members of the burial community are far less conspicuous in terms of variety and fossil density. The most striking element is an arthropod, a medium-sized phyllocarid of the species *Concavicaris sinuata.* It occurs, at the site of Mecca Quarry, in notable abundance in two narrowly limited levels only (see fig. 32). In addition, there are conodonts, some cephalopods, orbiculoid brachiopods (rare), sponges (rare), two specimens of an oligochaete worm (pl. 21, C), and a number of problematica. *Dunbarella,* so characteristic an element in level D, does not extend beyond the sharp bedding plane separating levels D and C. Only a single fragment of a *Dunbarella* shell was discovered in level A3.4 of the Mecca Quarry.

The thanatocoenosis consists of organisms capable of active or passive movement (by floating or rafting). The analysis of the causes of death (p. 134) and mode of burial and preservation (p. 129) leave little doubt but that this is also an autochthonous burial assemblage.

The question as to what proportion of the animal community present at the time in the Mecca Quarry area joined the burial community is an intriguing one. On the one hand soft-bodied and extremely delicate worms were preserved, but only the (presumed) fin spines and the skin denticles are known of *Listracanthus* and *Petrodus;* not a trace of the rest of these animals has withstood the degradation process. While it is thus possible that some types of soft-bodied animals are missing in the burial community, it is virtually certain that all of those with hard parts and even those with fairly durable soft parts are represented. Since this burial community, although clearly of autochthonous origin,[1] consists of a selection of elements from an ecosystem of a different realm (see p. 198) it would seem probable that most of the macroscopic forms that entered the Mecca area became part of the burial community.

3. *BURIAL COMMUNITIES OF LOGAN QUARRY SHALE*

(a) THE BURIAL COMMUNITIES OF LEVELS M AND L AT LOGAN QUARRY

Level M of the Logan Quarry is a gray shale beneath the thin seam of coal (see fig. 16). It was sampled in only two small areas of the quarry. Level M consists in a large measure of matted sticks and highly degraded plant remains, quantities of sulfides, and some clay. Poorly preserved remains of *Dunbarella* appear to be restricted to a zone a few millimeters thick near the top of level M. Other faunal remains noted were a coprolite and a single palaeoniscoid scale.

The poor state of preservation of these remains permits but few conclusions as to the character of the burial community. It seems to us that the general environment reflected by level M could hardly have been attractive for a marine pelecypod such as *Dunbarella.* It seems much more likely that the shells of dead animals were washed into the Logan Quarry area during a brief period when there was a connection between Logan and the shore of the sea a short distance to the west.

Level L consists of a basal black humulite covered by a dark gray to black, unevenly bedded shale. In the latter, fossils are apparently rare, but one well-preserved cephalopod and some fragments of *Dunbarella* were collected. Historically this shale represents the transgression shell breccia of the Mecca Quarry shale, but it contains little broken shell debris.

(b) THE BURIAL COMMUNITY OF LEVELS Kb TO F AT LOGAN QUARRY

This section of the Logan Quarry profile consists of even-bedded sheety shales of alternating gray and black horizons. The burial community resembles that of levels C to A of the Mecca Quarry so far as the vertebrates are concerned. The proportion of the various elements to the total number of specimens, however, differs from that of the Mecca Quarry (fig. 41), and so does the quantitative distribution of mutilated specimens, regurgitated specimens, gastric residues and coprolites, although the latter two categories are somewhat biased by the fact that not all such remains were collected (fig. 42). Moreover, the scarcity of *Petrodus* denticles and *Listracanthus* spines at Logan Quarry as well as the presence of some large sharks and an acanthodian of enormous size[2] are notable differences in the burial communities of the two environments.

As to the invertebrates, there are further differences between Logan Quarry and Mecca Quarry. *Concavicaris,* while present at Logan Quarry, is represented by only eight fragmentary specimens. On the other hand, goniatites of two genera occur as whole shells in modest numbers at Logan Quarry; none could be identified from Mecca Quarry. Furthermore,

[1] In the sense that the animals lived in the area of the burial ground prior to death.

[2] Unfortunately, known only from a short portion of the vertebral column and a large number of scales.

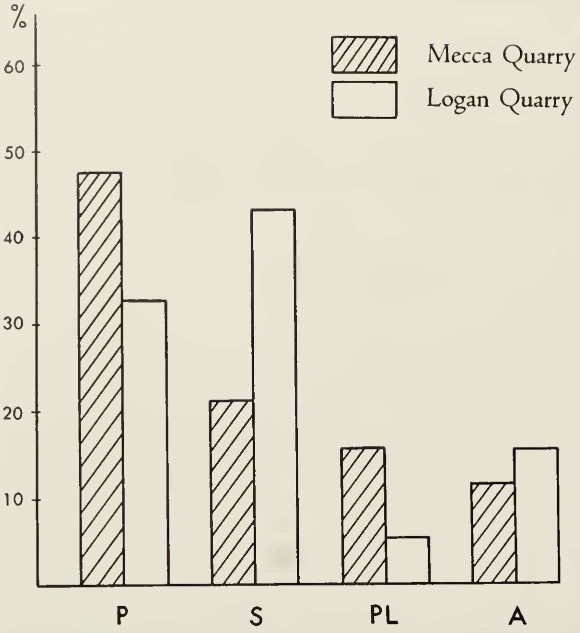


FIG. 41. Comparative abundance of palaeoniscoids (P), sharks (S), "placoderms" (PL) and acanthodians (A) in Mecca and Logan Quarries.

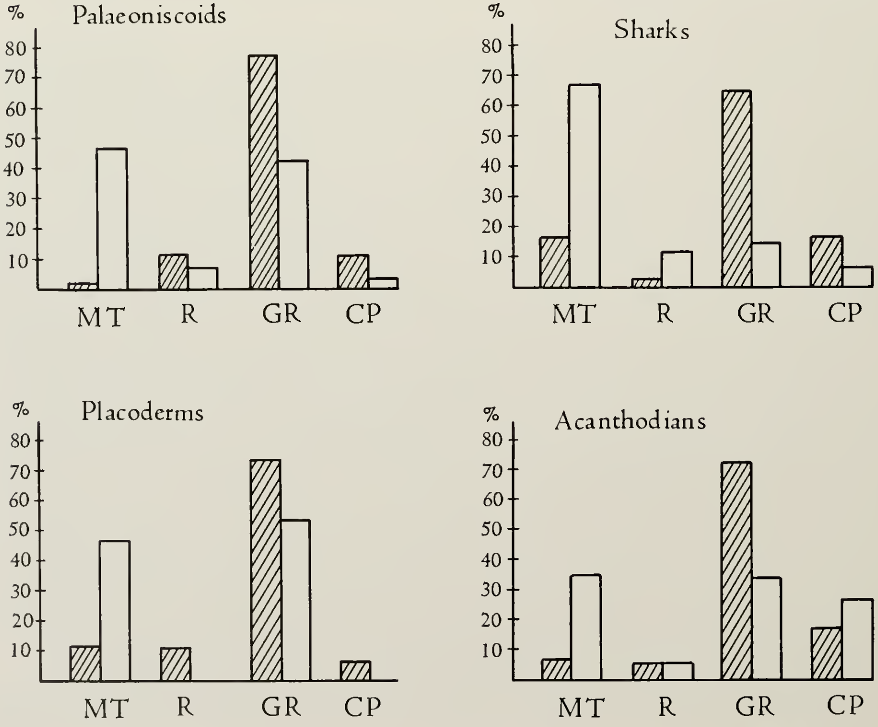


FIG. 42. Comparative abundance of mutilated specimens (MT), regurgitated specimens (R), gastric residues (GR) and coprolites (CP) in Mecca (shaded columns) and Logan Quarries.

coiled cephalopods of very large size (up to 3 feet in diameter) are quite common in level F at Logan Quarry and these forms also seem to be absent in the Mecca Quarry.

A comparison between the burial communities of levels Kb to F (Logan Quarry) with those of levels D to A (Mecca Quarry) thus reveals some qualitative and marked quantitative differences, but the overall aspect of the two assemblages is nevertheless similar. The assemblages represent two samples from a single biotope.

(c) THE BURIAL COMMUNITY OF ZONES 4 TO 6, GARRARD QUARRY

The burial community of this section of the Logan Quarry shale profile at Garrard Quarry (fig. 16) is of an entirely different character from that of the overlying Zones 7 to 9 and all levels at Logan Quarry except the base of level L. It consists of countless shells of *Myalina*, a smaller number of *Lingula*, a few snails, a delicate percarid crustacean, a variety of small palaeoniscoids, a large rhipidistian,[1] a fresh-water pleuracanthid shark,[2] and an acanthodian which is probably the same species as the common form from the Mecca and Logan Quarries. The latter is the sole element of the fauna present in both burial environments. The total absence in Zones 4 to 6 of the characteristic marine elements present at Logan Quarry and, conversely, the total absence (with the exception of the acanthodian) of any of these faunal elements at Logan Quarry, only one-half mile to the southwest, indicate that this fauna is a fresh-water assemblage. The nature of the sediment (p. 135), furthermore, suggests that the burial community is autochthonous in character.

The density of the burial community of *Myalina* in Zones 4 and 5 is extremely great, decreasing sharply in Zone 5 and reaching zero at the top of that zone. The burial density of all other elements of the fauna in Zones 4 to 6 is low compared to Logan or Mecca Quarry.

In Zone 6 there is a variety of small but well-preserved remains of leaves and stems (pl. 21, B); the former have been identified as belonging mostly to *Sphenopteris* and *Pecopteris*.

Within the topmost few millimeters of Zone 6 there appears a mixture of marine and fresh-water elements: linguloids as isolated individuals, or in one case in a large cluster of many individuals (pl. 23, C, D), and an occasional *Dunbarella* fragment are found mixed with occasional *Myalina* shells, small palaeoniscoids and the percarid. Scarce remains of acanthodians were recovered from Zones 4, 5, and 9.

(d) THE BURIAL COMMUNITY OF ZONES 7 TO 9, GARRARD QUARRY

Zones 7 to 9 of the Garrard Quarry profile contain a marine burial community consisting primarily of *Dunbarella* and cephalopods. *Dunbarella* occupies Zones 7 and 8 in great burial density; cephalopods are rare. The cephalopods are moderately common in Zone 9, and *Dunbarella* is uncommon.

(e) THE BURIAL COMMUNITIES, MOLLUSCAN FACIES, LOGAN QUARRY SHALE

At Haworth Creek, as at Garrard Quarry, the humulite is succeeded by sheety shale containing vast quantities of pelecypods. At Garrard Quarry these are entirely *Dunbarella;* at Haworth Creek there is a succession in the sense that *Dunbarella* is replaced in prominence by *Pteria* in the upper part of the pelecypod sequence. At Big Pond Creek the pelecypod community appears to have the same relations as at Haworth Creek and Garrard Quarry, but it occupies a much thicker section of shale. In nearly all places a *Dunbarella* burial community pioneers the transgression sequence.

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[1] Represented by some skull bones, large scales and teeth.

[2] Represented by numerous teeth only.

Table 10.—CLASSIFIED REMAINS AT MECCA AND LOGAN QUARRIES

Classified remains	Mecca Quarry		Logan Quarry	
	No.	%	No.	%
Palaeoniscoids:				
mutilated	6	1.7	108	46.4
regurgitated	40	11.4	18	7.7
gastric residues†	268	76.3	99	42.5
coprolites†	37	10.5	8	3.4
Total	351	47.7*	233	33.9*
Sharks:				
mutilated	28	16.6	205	67.2
regurgitated	4	2.4	37	12.1
gastric residues†	109	64.5	44	14.4
coprolites†	28	16.6	19	6.2
Total	169	23.0*	305	44.4*
"Placoderms:"				
mutilated	13	10.4	13	46.4
regurgitated	14	11.2	—	—
gastric residues†	91	72.8	15	53.6
coprolites†	7	5.6	—	—
Total	125	17.0*	28	4.1*
Acanthodians:				
mutilated	6	6.6	42	34.7
regurgitated	5	5.5	6	5.0
gastric residues†	65	71.4	41	33.9
coprolites†	15	16.4	32	26.4
Total	91	12.4*	121	17.6*
Total palaeoniscoids+sharks+"placoderms"+acanthodians	736		687	
Mixed gastric residues and coprolites, but not purely fecal coprolites	77		32	
Total all categories	813		719	

* % of total number of palaeoniscoids, sharks, "placoderms," and acanthodians.

† classified according to what they contain, not who produced them.

In these three places the pelecypod community was succeeded by a more varied community that approaches in character and composition that of level D of the Mecca Quarry shale, including cephalopods and a few vertebrates.

4. *DENSITY OF BURIAL POPULATION AT MECCA AND LOGAN QUARRIES*

It was pointed out above that there is strong evidence for the conclusion that the elements of the burial community in the Mecca and Logan Quarry areas reflect rather closely the make-up of the living assemblages of macroscopic organisms that entered the regions of the two sites. An appraisal of the density of the burial community should provide us with an estimate as to the quantitative relationships between the burial populations and the living populations in the Mecca and Logan Quarry areas.[1]

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[1] We are fully aware of the fact that such a relationship cannot be determined except under the most unusual circumstances.

The fossil density, especially in the black levels of the Mecca Quarry shale, is very great indeed. This is borne out by the actual count of specimens and debris as recorded for all quarter-inch levels of the shale profile (except level C) (see fig. 32). The number of remains recorded in this manner obviously exceeds the number of individuals represented in the burial community. The collecting procedure followed during the reduction of the quarry shale (see p. 10), however, provided the raw material for an estimate of the number of individuals buried per unit volume of shale, at least so far as the vertebrates are concerned. In the Logan Quarry it was likewise the black levels G and J that contained the greatest vertebrate concentrations. The nature of the carcass remains at this site was found to be so similar to that of the Mecca Quarry that the following calculations on the density of the burial population may be based on the same premises as are applicable to the Mecca Quarry material. All specimens were identified in terms of their nature as carcass remains (p. 139) and the number of specimens in each category is compiled in Table 10.

The total number of vertebrate specimens (not individuals) collected from the Mecca Quarry shale sample is 813. The quarry shale sample comprises about 6.7 m^3 (see p. 8, dimensions of quarry). The fossil density of the shale at Mecca Quarry thus amounts to 121.3 specimens per m^3 of shale. The number of specimens for the Logan Quarry is 719. The shale sample is about 204.5 m^3 (see p. 14, quarry dimensions). The specimen density at Logan Quarry is thus about 3.5 per m^3 of shale.

The figures in Table 10 lend themselves to an estimate of the number of individuals represented by the 813 and 719 specimens collected in the two quarries by considering mutilated and regurgitated specimens as representing one individual each, and assuming that gastric residues represent (on the average) ½ individual each, and disregarding all coprolites, isolated skeletal elements and mixed gastric residues.

The resulting estimates tend to be on the conservative side, since isolated skeletal debris (including *Listracanthus* and *Petrodus*) makes up a large portion of the fossil content, particularly at Mecca Quarry. Some of this debris, however, may safely be assumed to have belonged to specimens that are included in the counts of Table 10.

For the Mecca and Logan Quarry shale samples, the following figures result:

Classified remains	Mecca Quarry	Logan Quarry
mutilated specimens (1 each)	53	368
regurgitated specimens (1 each)	63	61
gastric residues (½ each)	266	99
Total	382 individuals per 6.7 m^3 of shale	528 individuals per 204.5 m^3 of shale

or 57 individuals per m^3 for the Mecca Quarry and 2.6 individuals per m^3 for the Logan Quarry. These values, although expressing the fossil content in terms of individuals per unit volume of shale, do not have any direct ecological usefulness. A more meaningful value would be the number of individuals that were buried in the course of a year per unit area of burial ground. According to the determination of the rate of deposition of the Mecca Quarry sediment (fig. 39) a period of about four years was required for the deposition of the 12 inches of shale. For the Logan Quarry shale (at the site of Logan Quarry) a depositional cycle of three years seems indicated (p. 29). The desired values can thus readily be calculated:

Mecca Quarry: 382 individuals per 20 m^2 per 4-year period, or,
95 individuals per 20 m^2 of burial ground per year.[1]

Logan Quarry: 528 individuals per 450 m^2 per 3-year period, or,
176 individuals per 450 m^2 of burial ground per year.[1]

To render these values comparable they may be calculated to uniform area, for example, 100 m^2 as follows:

Mecca Quarry: 475 individuals per 100 m^2 of burial ground per year.

Logan Quarry: 39 individuals per 100 m^2 of burial ground per year.

5. *RELATIONSHIP BETWEEN BURIAL AND LIVING POPULATIONS*

The question arises as to the relationship of the above values to the number of individuals that were living at any one time over the burial ground. In neither the Mecca nor the Logan Quarry shale profile is there any evidence of mass mortality or destruction of the entire population living in these areas. Carcasses were continually supplied from a reservoir of living animals; gastric residues and coprolites extend throughout the profile, indicating that living animals were present at all times. There is, furthermore, very strong evidence for the conclusion that none of the vertebrates died of causes other than the activity of predators (see p. 139). For these reasons alone we must assume that the living populations were greater than the burial populations. It would seem impossible to arrive at an accurate estimate of the magnitude of this difference at any given moment in time. An estimate of this sort, however rough, nevertheless is desirable not only in terms of density of the living populations in the Mecca and Logan areas but also as an additional line of evidence for the interpretation of the local environment. When the Mecca and Logan environments are viewed in their entirety there can be no reasonable doubt that they were shallow, representing as they do the very initial phases of marine transgressions over a coastal coal forest.[2] Any estimates as to the depth of water at the sites of Mecca and Logan Quarries must lie within feet and inches rather than tens of feet. The living population at these sites was thus restricted to a thin layer of water, at least during the dry seasons (see pp. 23, 31). Since the bulk of the burial populations is enclosed in the black levels of the shale profiles (which represent the dry periods of the seasonal cycle) we can determine whether or not any crowding of the populations occurred during these times by calculating the ratio between the volume of the burial population and the volume of water in which it lived. Since the burial population was probably smaller than the living population such resulting ratios should be minimal rather than maximal values. The calculation requires assumptions and estimates of values of the following: the average weight of the fishes in each principal category (sharks, "placoderms," palaeoniscoids and acanthodians), the average density (grams per cc.) of these fishes, and the depth of water over the Mecca and Logan Quarry areas.

	Average Weights	
	Low estimate Kg.	High estimate Kg.
Sharks	2	40
Acanthodians	.25	1
"Placoderms"	.25	2
Palaeoniscoids	.10	.50

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[1] Average values for the periods.

[2] The contention that great tectonic movements might have produced deep basins remains totally unsupported by any evidence.

Average weight estimates of the fishes were made by comparison with modern forms of similar size and shape; there are, however, many uncertainties in such a procedure and for this reason the calculations are based on two sets of figures, one certainly too low, the other probably too high, as above.

The density of a variety of modern fishes and various parts of fishes has been determined by Lowndes (1955). The density of the Mecca shale fishes was probably slightly higher than the values for the modern forms for which these values have been determined, since most of them are rather heavily armored. Based on Lowndes' figures an average density of 1.085 grams/cc. seems reasonable for the Mecca fishes.

The layer of water over the Mecca and Logan Quarry areas during the dry seasons was very shallow; furthermore, only a fraction of the depth (a thin layer near the surface) may be considered as having been sufficiently aerated to permit the existence of a dense animal population (see p. 31). For the purpose of the calculation two assumptions were made. One was minimal (1 foot), the other probably maximal (3 feet).

Mecca Quarry: The weight of the burial population of 100 m^2 per year, 475 individuals, for the low and high weight estimates, results in the following figures:

	Weight of Burial Population			
		Low estimate Kg.		High estimate Kg.
Sharks (105)	@ 2 kg.:	210	@ 40 kg.:	4200
Acanthodians (55)	@ .25 kg.:	13	@ 1 kg.:	55
"Placoderms" (90)	@ .25 kg.:	22.5	@ 2 kg.:	180
Palaeoniscoids (225)	@ .1 kg.:	22.5	@ .5 kg.:	112.5
Total (475)		268.0		4547.5

$$\frac{\text{weight}}{\text{density}} = \frac{268.0}{1.085} = 247.0 \text{ dm}^3$$

or 9.15 cubic feet of fish

$$\frac{\text{weight}}{\text{density}} = \frac{4547.5}{1.085} = 4191.2 \text{ dm}^3$$

or 155.23 cubic feet of fish

The volume of water over one hundred square meters of area for the minimal and maximal estimates amounts to:

Low estimate, 1 foot	High estimate, 3 feet
100 m^2 × .33 m = 33 m^3	100 m^2 × .99 m = 99 m^3
or about 891 cubic feet	or about 2673 cubic feet

The combination of the above values for low and high estimates results in the following four ratios:

	Volume of water (a)	Volume of fish (b)	Volume of water between fishes (c=a–b)	The ratio between volume of fish and volume of water at their disposal (in rounded figures) (b:c)
low:low	891	9.15	881.85	1:96
low:high	891	155.23	735.77	1:5
high:low	2673	9.15	2663.85	1:291
high:high	2673	155.23	2517.77	1:16

Logan Quarry: Comparable calculations for the Logan Quarry material result in the following values (burial density, 39 individuals per 100 m^2 per year):

	Weight of Burial Population			
	Low estimate		High estimate	
		Kg.		Kg.
Sharks (20)	@ 2 kg.:	40	@ 40 kg.:	800
Acanthodians (5)	@ .25 kg.:	1.25	@ 1 kg.:	5
"Placoderms" (1)	@ .25 kg.:	.25	@ 2 kg.:	2
Palaeoniscoids (13)	@ .1 kg.:	1.3	@ .5 kg.:	6.5
Total (39)		42.8		813.5

$$\frac{\text{weight}}{\text{density}} = \frac{42.8}{1.085} = 39.44 \text{ dm}^3$$

or: 1.46 cubic feet of fish

$$\frac{\text{weight}}{\text{density}} = \frac{813.5}{1.085} = 749.76 \text{ dm}^3$$

or: 27.7 cubic feet of fish

Using the same values for the volume of water as for the Mecca Quarry (above), the four combinations are as follows:

	Volume of water (a)	Volume of fish (b)	Volume of water between fishes (c=a−b)	The ratio between volume of fish and volume of water at their disposal (in rounded figures) (b:c)
low:low	891	1.46	889.54	1:609
low:high	891	27.7	863.3	1:31
high:low	2673	1.46	2671.54	1:1830
high:high	2673	27.7	2645.3	1:95

It would seem that the (unknown) correct value lies somewhere between the high: low and low: high values.

To gain some idea as to the meaning of these figures, comparable calculations were made from data for two experimental fish ponds that were permitted to become overcrowded and were subsequently drained and the fishes weighed. The data are taken from Swingle and Smith (1940, Table 3, p. 274).

	Pond 1	Pond 2
Area of pond	1 acre (4050 m^2)	1.8 acres (7290 m^2)
Age of pond	3 years	3 years
Weight of fish	580 lb. (263.1 kg.)	478 lb. (216.8 kg.)
Density of fish (estimate) (from Lowndes)	1.075 g./cc.	1.075 g./cc.
Volume of fish	244.74 dm.^{3} (9.1 ft.^{3})	201.67 dm.^{3} (7.5 ft.^{3})
Volume of fish per 100 m^2 (depth, 1 ft.,[1] 891 ft.^{3} of water)	0.224691 ft.^{3}	0.10286 ft.^{3}
Volume of water between fishes (volume of water minus volume of fish)	890.78 ft.^{3}	890.9 ft.^{3}
Ratio between volume of fish and volume of water at their disposal (in rounded figures)	1:3964	1:6613

In view of these values in overcrowded experimental fishponds, we conclude that the population density at Logan Quarry—and to a far greater extent at the Mecca site—reflects extreme crowding. We have, however, no evidence that the crowding reached lethal proportions. During the drying of a populated pond, the fish and tadpoles may be observed to continue living until the volume of available water per animal becomes very small, perhaps approaching 1:1. Such conditions, of course, do not constitute a habitat that can be endured for more than a short period.

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[1] Loren P. Woods, Curator of Fishes, Chicago Natural History Museum, suggested that most of the fishes in ponds are distributed through the bottom foot of the water.

We may conclude from the above considerations that the density of the living population at Mecca Quarry could not have been much greater than that of the burial population.

6. *BIOLOGICAL IMPLICATIONS OF POPULATION DENSITY*

A fish population density of the magnitude suggested by the values calculated for the Mecca Quarry area has a number of biological implications. Although many species of fishes tend to congregate in large schools sufficiently dense to be recorded by modern sounding devices, such schools consist primarily of individuals of a single species. Schools consisting of elements similar (ecologically more or less comparable) to those of the Mecca assemblage have never been observed, to our knowledge. It seems very unlikely that the population density at Mecca had anything whatsoever to do with schooling behavior.

The extreme crowding of the population poses the problem of the availability of sufficient oxygen for the survival of the individuals. The microscopic structure of the shale (p. 105) indicates a bottom mud in which decomposition of vast amounts of plant and animal remains must have virtually exhausted all of the available oxygen. Four factors indicate that the environment was protected from wave action: the deduced local source of plant debris (see p. 120), the fine bedding of the shale, the lack of vertical spread of parts from individual vertebrate specimens and lack of directed orientation of debris particles in the sediment. Thus we are led to the conclusion that a floating mat of vegetation must have extended over or just under the water surface (p. 121, *flotant*). Modern environments of this general type are severely deoxygenated and can support only a very limited number of species of fishes that are especially adapted to this kind of situation (see Carter, 1955 and 1960).

Great population density and an environment such as seems indicated for the Mecca example are, however, not entirely irreconcilable conclusions. It is highly probable that the fishes in this assemblage were forms that had very low oxygen requirements, on the order, for example, of those of the modern carp. If the *flotant* consisted of filamentous algae —and this seems a likely possibility—it would have reduced the carbon dioxide tension to some extent as well as introduced oxygen into the surface water.[1] The ratio between water surface and depth of water (probably no more than two feet) favored the aeration of the water beneath the *flotant*. The relative scarcity of sulfides in the shale (as compared with the situation at Garrard Quarry; see below) suggests that there was a very slow groundwater flow toward the sea that removed the noxious decomposition products and introduced better aerated surface water from landward, flowing through *flotant* almost in contact with the bottom (p. 154). Finally, rainwater may have added a significant amount of air to the Mecca environment.

The crowding of the fish population in the Mecca area raises the further question as to the food supply.

7. *FOOD RELATIONSHIPS AND FEEDING BEHAVIOR*

The food relationships among the faunal elements of Mecca and Logan Quarries appear to be rather similar and may thus be described together. The overall food picture is dominated by the fact that apparently none of the vertebrates (and perhaps none of the invertebrates that joined the burial community) died of causes other than the direct or indirect effects of predation. It was set forth above (p. 139) that the vertebrate specimens may be classified, according to the nature of the carcass remains, as mutilated individuals, regurgitated individuals, gastric residues and coprolites. All faunal elements, including the predators, are found among these categories. The size relationships among the vertebrate elements and their carcass remains leave no doubt that the medium- to large-sized sharks were the principal fish predators. Very little may be said about the minor predators among the fishes, the palaeoniscoids, and there is no evidence at all about the food habits of the "placoderms" and the apparently toothless acanthodians.

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[1] At night, however, aquatic plants tend to build up CO_2 tension in water.

(a) PRIMARY PRODUCERS AND SMALL SECONDARY PRODUCERS AND CONSUMERS

In order to support the enormous concentration of fishes, the Mecca and Logan sites must have produced large quantities of food in the form of primary and secondary producers and small consumers, but these have left no identifiable traces in the sediments.

The high content of carbonaceous material in the black shale levels, the absence of currents strong enough to have accumulated decomposing material from elsewhere, and the totally undisturbed character of the shale led to the conclusion that the Mecca and Logan environments were covered by floating mats of vegetation (of unknown botanical character, but most likely algal). Further indirect evidence for such an interpretation arises from the obvious necessity for sufficient local food production to have sustained the great population density of the vertebrates. A floating mat of vegetation, itself a primary producer, could have supported and harbored a host of secondary producers and small consumers. The latter apparently did not include small species or immature individuals of larger species of fishes,[1] but it would seem likely that the phyllocarids, the orbiculoid brachiopods, and probably even the linguloids were closely associated with the *flotant*.[2]

(b) MEDIUM-SIZED CONSUMERS

The palaeoniscoids, "placoderms," acanthodians and small sharks fall into this category. A large number of small coprolites ranging in volume from about ¼ cm.^{3} to about 1 cm.^{3} collected from the Mecca shale probably were produced by these fishes, as would seem reasonable from the size relationships, as follows: palaeoniscoids, percoid-shaped, maximum observed length about 280 mm.; acanthodian, eel-shaped, no complete specimens, maximum observed length 350 mm., probably 400 mm. or more; "placoderms," tadpole-shaped, about 300 mm. in length or less; small shark (cf. *Denea*), no articulated specimens, estimated length 350 to 450 mm.

In thin section these small coprolites rarely appear as homogeneous fecal masses, even if they contain no skeletal material. In some of them at least three quite sharply delimited fecal components may be distinguished by color differences and by the interesting fact that the pyrite crystals in these components are of notably different size. This is probably the result of extremely limited microenvironmental relations in fecal matter of possibly different origin, chemical content and diffusion characteristics. Embedded in the fecal matrix there are occasional inclusions suggestive of animal remains, but these are rarely identifiable.

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[1] While the present collection does include a few immature individuals, it does not seem reasonable to suppose that fish fry constituted an appreciable portion of the food supply; very few immature individuals were seen in gastric residues.

[2] Modern lingulas are attached to the bottom mud. All our evidence concerning bottom conditions and character of mud at Mecca and Logan Quarries renders a similar interpretation all but impossible here.

In none of the coprolite sections studied could vegetation be definitely identified as the original food material, but this is very probably due to our lack of knowledge of modern fecal masses. In some sections, notably no. 152, the fecal material appears fibrous and is richly red-brown in color, thus suggesting possible plant origin.

Small coprolites that contain remains of vertebrates show the effects of digestion on these structures: some peripheral etching and internal loss of structural details. There appears to be no evidence, however, to suggest that bones and scales were actually dissolved in the digestive process. Evidence of mechanical destruction of spongy bone is seen in section 147; almost the entire coprolite consists of spongy palaeoniscoid bone, most of which, but not all, appears badly broken. Of special note is the fact that the skeletal pieces (and the bone cavities, in so far as they have not been crushed by mastication) are not impregnated with either fecal ground substance or shale matrix, nor are they filled with mineral (see p. 178, for depositional significance of this type of preservation).

The evidence presented indicates that the medium-sized vertebrates consumed a variety of foods, but it is impossible to determine precisely what types, except that it did include other medium-sized vertebrates. Since none of them are equipped with mouths large enough to swallow each other whole, nor provided with suitable teeth to seriously mutilate each other, we must conclude that they availed themselves of food provided by the sharks which killed and mutilated many individuals, often without ingesting the prey (see p. 137). Yet there is no evidence of scavenger action at the bottom. Feeding by the medium-sized vertebrates must thus have taken place almost simultaneously with the predatory activity of the sharks, before the leftovers of the prey had time to settle out of reach.

To what extent this feeding behavior reflects a scarcity of the natural food elements of these fishes is not certain, in view of the fact that we know virtually nothing about the small consumers that very probably were present in these environments. It seems to indicate abnormal conditions, however, that might have been related to the extreme population density of the fishes, which would have reduced the natural food supply and provided a new source of food in the wasteful predatory activity of the sharks.

(c) THE LARGE PREDATORS

Perhaps the most striking aspect of the food relationship among the fishes of the Mecca and Logan Quarry sites lies in the fact that the large predators—sharks 3 to 12 or more feet in length—have joined the burial community as prey, in very large numbers (fig. 42).[1] This fact alone, we believe, strongly suggests that the Mecca and Logan Quarry environments *do not* reflect conditions resulting from balanced eco-systems. In a balanced system of trophic relationships the main predators would hardly figure among the principal food sources. This, however, is clearly the case at the Mecca and Logan sites.

A superficial appraisal of the vertebrate fossils identified as mutilated specimens, regurgitated specimens, gastric residues and coprolites would seem to indicate indiscriminate and wasteful feeding behavior on the part of the predators. Closer examination of the large prey (5- to 6-foot sharks) reveals, however, that the point of attack upon the prey was not wholly a matter of chance.

This is supported by the following figures from Logan Quarry based on examination of specimens in various states of preservation:

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[1] The values in figure 42 include the small sharks, but these are not common enough to change the picture materially.

MUTILATED SHARKS	Number
Near-complete skeletons	45
Skulls only (with or without shoulder region)	66
Tail fins only	61
Odd parts of skeleton	33
Total	205

The large number of amputated heads and tails suggests that the predators attacked their prey at the mid-section of the body—the area containing the viscera (especially the liver) and most of the axial musculature. This conclusion is in accord with observations on modern sharks, kindly related to us by personal communication by Dr. Perry W. Gilbert of Cornell University, who stressed the point that sharks tend to attack their prey from above: "It is not at all uncommon for sharks to prey on each other, even their own species. When we have trouble getting large sharks to feed in our experimental shark pens at the Lerner Marine Laboratory, we usually toss in a few young sharks, and these tidbits the adult sharks find irresistible. They promptly take out after them, approach them from above, and consume them in a single gulp, or at most, two bites."

Dr. Gilbert also writes in part: "The tiger shark *Galeocerdo cuvieri* is particularly notorious in attacking other members of its own species when hooked. Usually, it attacks at the midpoint of the body on the back, i.e., roughly halfway between the tip of the snout and the tip of the tail."

The direction of approach of the predator, from above the prey, may explain the disproportionate absence or mutilation of the dorsal lobes of the tail fins at Logan Quarry:

AMPUTATED SHARK TAIL FINS	Number
Dorsal and ventral lobes articulated	11
Ventral lobes articulated, dorsal lobes disarticulated or missing	36
Dorsal lobes articulated, ventral lobes disarticulated or missing	3
Both lobes more or less disarticulated	11
Total	61

Much of the feeding activity of the sharks is evidenced by the gastric residues and the coprolites. The character of these fossils is described above (p. 140). While the coprolites tend to give little information as to the nature of the ingested food, the gastric residues almost invariably contain the skeletal remains of the prey.

Most of the gastric residues in the collection from Mecca and Logan Quarries are of a size range that clearly excludes all but the medium and large sharks as the producers. In these gastric residues all major faunal elements of the sheety black shales are represented with the exception of *Petrodus*. Of all the thousands of *Petrodus* denticles that were noted in the Mecca Quarry sample (fig. 32), not a single one was definitely identifiable as part of a gastric residue. *Listracanthus*, likewise very common at Mecca, was observed only three times in gastric residues. This indicates that *Listracanthus* was essentially inedible, while the absence of *Petrodus* from these residues is probably related to the large size of the animal.[1] The size of *Petrodus* is not known, but from West Montezuma we collected a slab of black sheety shale containing a mixed aggregation of countless *Petrodus* denticles both large and small (presumably representing shagreen elements from the dorsal and ventral parts of the skin) and a large number of *Listracanthus* spines. The mixture of these elements tends to suggest that the specimen represents ill-packed gastric residue from a predator of enormous size. Very large gastric residue pellets containing packed *Petrodus* denticles, shark fin spines, edestid tooth spines, "placoderm" bones and teeth, palaeoniscoid bones and scales, acanthodian spines, and broken cephalopod shells were collected from the roof shale presumably of a coal mine at or near Newport, Indiana.[1] These specimens not only testify to the presence of giant predators,[2] but suggest that *Petrodus* itself was eaten only by them.

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[1] With the exception of a single instance, no placoid scales of large sharks like the one from Logan Quarry (PF 2201; pl. 24, B) were seen in gastric residues.

Gastric residues of sharks sometimes contain broken and degraded cephalopod shells and, more rarely yet, recognizable bits of phyllocarid tests; in the Mecca Quarry, especially in the levels in which phyllocarids occur commonly, a great number of very thin, small areas (about 5 cm. in diameter) of rugose surface texture were noted. In a few of these rugose areas badly degraded phyllocarid remains could be discerned. It is possible that these areas represent gastric residues from small sharks that had eaten phyllocarids, but there are uncertainties in this interpretation.

That phyllocarids were eaten by the smaller sharks, however, is certain. In one almost perfectly preserved specimen (PF 2469) from Logan Quarry, gastro-intestinal content is seen *in situ* and it contains an almost unbroken phyllocarid specimen, as well as a mass of palaeoniscoid scales.

Gastro-intestinal content is preserved in place in a number of shark specimens, for example, in PF 2202 (fig. 38), where the nature of the food cannot be made out from the radiograph, and in a specimen (PF 2207) of *Stethacanthus*,[3] in which a well-defined mass of intestinal content is located anterior to the pelvic elements and terminates in a sharply outlined spiral coprolitic mass in the pelvic area.

One of the rather astonishing aspects of the gastric residues from Mecca and Logan Quarries is the fact that the enclosed skeletal remains do not show any appreciable amount of etching. Modern sharks are reported to have notable concentrations of hydrochloric acid (up to 1 per cent) in their stomachs (Barrington, 1957), and Gudger (1949) reports a dehorned cow skull and a horse skull in stomachs of *Galeocerdo tigrinus* that showed a marked degree of solution.

The fact that not only dense scales but also delicate palaeoniscoid skull bones present in many gastric residues show little if any evidence of exposure to acid tends to suggest that gastric digestion in these Paleozoic sharks might have differed from that of modern forms in that the HCl concentration was notably lower, as in fact it is in most other fishes

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[1] These specimens are part of the Walker Museum (University of Chicago) collection and were obviously collected a long time ago. We were unable to determine the exact source of these specimens, or the stratigraphic horizon. In the latter part of the nineteenth century there was considerable coal mining activity in the vicinity of Newport.

[2] The postulation of animals of giant size is based on rather good evidence. At Logan Quarry an articulated shark (PF 2201, pl. 24, B) measures 8½ feet from the snout to a point anterior to the pelvic fins; the whole animal may be estimated to have measured 13 or more feet in length. A pair of articulated lower jaws (PF 2206) has a ramus length of 16 inches and a distance between articular facettes of about 18 inches; these clearly indicate an animal of very large size. At Logan Quarry we collected a specimen consisting of a great number of large acanthodian scales and a piece of vertebral column about one foot long. In shape and histological character these scales are virtually identical with those of the common small acanthodian. What is presumed to be the dorso-ventral dimension of the vertebral column measures about 45 mm.; the diameter of the scales is 3.5 mm. The scale diameter of the largest scales of the common acanthodian in the deposit is .25 mm. The scales of the large form are thus 14 times (in linear dimension) the size of those of the smaller species, which probably reached 2 or 3 feet in length. Even if it be granted that the size differential between these scales cannot be assumed to have been proportional to the overall sizes of the two species, it would seem obvious that the large form was a very large animal, probably of the habitus and proportions of a modern ribbon-fish.

[3] The genus *Stethacanthus* is based on a characteristic spine; such a spine is associated with this skeleton.

(Barrington, 1957). There is a distinct possibility of a correlation between the regurgitation[1] of hard-to-digest food residues and a low level of acid concentration in the stomachs of these sharks. Some, usually small, skeletal ingredients of food residues, however, did occasionally pass into the intestine, where they were severely affected by the digestive process. The surfaces of such elements are badly corroded and the histological structure of the elements is often no longer recognizable.

8. *ORIGIN OF BURIAL COMMUNITIES*

The characteristic burial community of the sheety black shales of Mecca and Logan Quarries consists of elements that have invaded these environments from elsewhere. Since these communities are characterized by a variety of sharks, the pectinoid *Dunbarella,* and cephalopods we may conclude that the assemblage, in all probability, originated in the marine waters of the epicontinental sea to the west. This supposition was vastly strengthened by the discovery of an entirely different burial community in the humulite at Garrard Quarry (see p. 187).

Of the entire humulite fauna as recorded, only the acanthodian occurs in the sheety shales at Logan Quarry, one-half mile away and in the same stratigraphic horizon. Conversely, with the exception of the acanthodian no traces of the elements of the burial community at Logan Quarry are represented in the humulite portion of the Garrard Quarry section. The close geographic juxtaposition of two entirely different burial communities is highly significant.

The stratigraphic sequence in the humulite portion of the Garrard section clearly indicates a fresh-water situation; all the evidence suggests that the burial assemblage is autochthonous, and pleuracanthid sharks are characteristic elements of fresh-water faunas. This evidence, together with the sharp contrast to the burial assemblage of nearby Logan Quarry, leaves, in our opinion, no doubt that the humulite assemblage represents a typical fresh-water community that lived there prior to the transgression.

Careful examination of the basal portions of the Logan Quarry shale at localities other than Logan Quarry proper, for example at Haworth Creek, north and south branches of Trumpet Valley, Woodland Valley and Dotson's Branch, revealed the presence of humulites similar to those at Garrard Quarry, containing the same fresh-water fauna. The Mecca Quarry shale, on the other hand, never (in the area of our study) overlies such a fresh-water section. Instead, it often overlies (locally) the channel clod, which contains purely marine elements dominated by productid brachiopods and corals. Channel clod was nowhere observed basal to the Logan Quarry shale.

K. COAL IIIA AND THE LOGAN QUARRY COAL

By

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The Mecca Quarry black shale studied so intensively in this report lies immediately above Coal IIIA throughout Parke and Vermillion counties. Coal IIIA is not known to be more than 2 feet thick anywhere in these counties and commonly ranges from 8 to 20 inches in thickness. To obtain information about geographic conditions that existed before deposition of the black shale, fifteen samples of this coal were collected from sites in Parke and Vermillion counties. The sample locations are listed in Table II and shown on the map (fig. 43). Two samples were collected at Montgomery Creek. One is overlain by sheety black shale; the other, from about 50 yards west of the first, is overlain by a channel filling, marine channel clod. Stratigraphic data, but no samples, were obtained from records of cores drilled in the region. The positions of these drill holes are designated as "C" locations on the map (fig. 43).

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[1] Regurgitation of stomach content has also been observed in modern sharks (Radcliffe, 1916, and others), but it is not believed to be a regular feature of the feeding behavior.

Table 11.—LIST OF SAMPLE LOCALITIES

Location Number	Designation	Location	Thickness of Coal (cm.)
1	Barren Creek	SW¼, sec. 28, T.15N., R.8W.	49.
2	Mecca (highway cut about 500 feet south of Mecca Quarry)	NE¼NW¼SE¼, sec. 29, T.15N., R.8W.	56.4
3 (A and B)[1]	Montgomery Creek	SW¼NW¼SE¼, sec. 30, T.15N., R.8W.	40.3 and 61
4	Dee Hollow	SW¼SW¼NE¼, sec. 19, T.15N., R.8W.	50.4
5	West Montezuma	NW¼NW¼, sec. 35, T.16N., R.9W.	26.
6	Arketex, old pit	NW¼SW¼SW¼, sec. 11, T.16N., R.9W.	19.
7	Arketex, new pit	NE¼SW¼SE¼, sec. 10, T.16N., R.9W.	20.2
8	Dead Man's Hollow	NW¼SW¼SE¼, sec. 4, T.17N., R.10W.	46.5
9	Hanging Rock	SE¼, sec. 20, T.18N., R.10W.	67.2
10	Little Vermillion River, south	NE¼NW¼NW¼, sec. 33, T.17N., R.9W.	26.0
14	Newport	NW¼SE¼SW¼, sec. 36, T.17N., R.9W.	36.6
15	Little Vermillion River	SE¼SE¼NW¼, sec. 28, T.17N., R.9W.	36.6
77	Drill core 77	SE¼SW¼, sec. 29, T.17N., R.10W.	42.8
78	Drill core 78	center, sec. 29, T.17N., R.10W.	45.7

[1] 3A beside a channel above the coal; 3B fifty yards away and directly below the channel.

As depositional history can only be interpreted from samples in which the vertical sequence is retained, all of the samples are oriented columns of the complete seam thickness. These columns were embedded in plaster, ground plane in vertical section, and polished. Routine examination was accomplished with the aid of a 30× binocular dissecting microscope and a small, bright spotlight. Thin sections were examined at higher magnifications.

To describe the depositional history, the contemporaneity of various levels of the samples had to be established. Ten of the 15 coal columns contain a clay parting that is less than 2 cm. thick. In many other coals, partings have been found to be ideal correlation layers. Thus if the Coal IIIA parting could be proved to be continuous, it could be used as the prime correlation layer here.

Most of Coal IIIA is finely banded and bright. As such, it is a normal coal. However, above the clay parting in each column there is at least one prominent layer consisting of the remains of cuticularized leaves. The exceptionally fine corrugation resulting from the cuticles standing out in relief is unmistakable when examined with the binocular microscope. Unfortunately, it is impossible to photograph this feature adequately. Plate 11, A, illustrates part of a thin section of one of these layers; their environmental significance will be discussed later.

The coal below the parting is predominantly finely striated and bright. However, in all ten of the parted samples, this lower bench contains several layers (normally between 0.5 and 2 cm. thick) which consist of dull attritus (see p. 207 for description of term). The depositional significance of these layers will be discussed later. Presently, it is sufficient to recognize that they stand out in sharp contrast to the normal, bright coal.

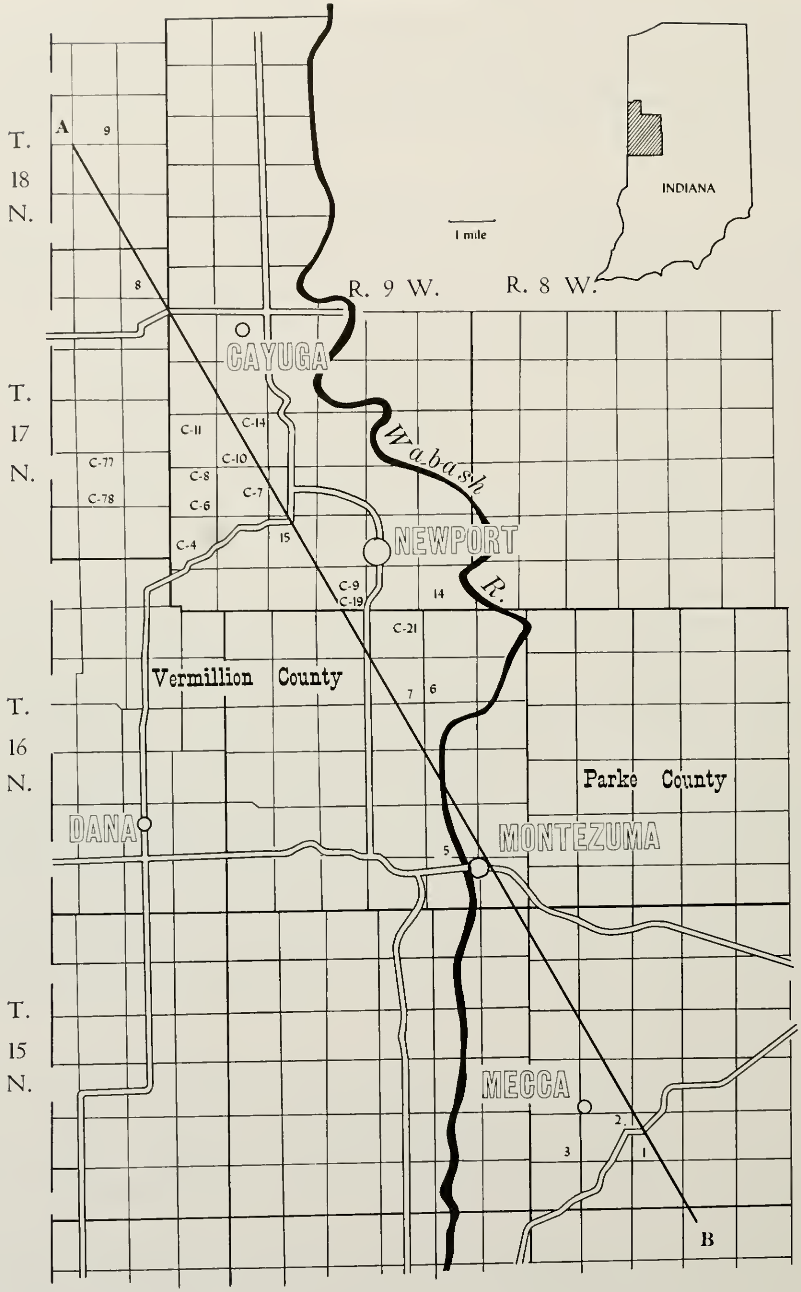

A
9
8
T. 18 N.
T. 17 N.
T. 16 N.
T. 15 N.
R. 9 W.
R. 8 W.
1 mile
INDIANA
CAYUGA
C-14
C-11
C-10
C-77
C-8
C-78
C-7
C-6
C-4
15
Wabash R.
NEWPORT
C-9
C-19
14
C-21
Vermillion County
7
6
Parke County
DANA
MONTEZUMA
5
MECCA
2
3
1
B

FIG. 43. Map showing source of coal samples. A–B, line of stratigraphic correlation (see fig. 45, *b*).

The fact that cuticle-rich layers are confined to the upper bench, and that dull attritus layers are confined to the lower bench (with a few exceptions), suggests that the respective upper and lower benches are contemporaneous in all ten samples. The remaining five samples contain cuticle-rich layers like those in the upper bench of the parted columns. Thus, the single-bench coal is probably correlative with the upper bench coal elsewhere. A thin, flaky shale lies between the underclay and the single-bench samples. This shale is probably correlative with the parting.

In order to further substantiate the correlation, G. K. Guennel, palynologist for the Indiana Geological Survey, examined maceration residues of several selected samples. The relative percentages of the spore genera (based on counts of 100 specimens per sample) are shown graphically (fig. 44, *a*). For a discussion of the classification system, see Guennel (1958, p. 37). The letter preceding most of the generic names indicates the plant type from which the spore was probably derived. Figure 44, *b*, shows the spore populations grouped according to these "parent" plant types. The two lower-bench samples appear to correlate. In both of these samples (which are from widely separated locations), "gymnosperms" are more abundant than ferns, and the sum of these two groups is greater than that of the other spores. In all of the other samples, except the Newport sample, ferns predominate over "gymnosperms." Variations in the lycopods alter the total distribution, but the fern-"gymnosperm" relation remains the same. These data suggest that the two lower-bench samples are similar and are distinct from the upper-bench and single-bench sample. The upper-bench and single-bench samples are similar.

Once the correlation of the parting is established, it then becomes possible to correlate the stratigraphic sections obtained from the area. Figure 45, *a*, shows all of the sections which have been obtained. Figure 45, *b*, shows only those sections within a mile of line A–B, figure 43. The sand and silt in the center of this cross section appear to have been deposited in a delta. The narrow distribution, upwardly decreasing grain size, and general shape (convex upward, areally linear) all suggest this conclusion. However, no bedding structures or textural features have been found which would indicate deltaic deposition. This latter fact suggests that deposition alternated with weathering, and from this it could be concluded that the delta was more nearly an alluvial fan. Friedman (1960) has presented evidence that the Coxville sandstone (at the same stratigraphic level, but 10 miles south) is also a deltaic deposit.

If it is accepted that the boundaries of the Pennsylvanian sea generally followed the present Pennsylvanian rock outcrop in the Illinois Basin, the geography of the study area prior to Coal IIIA time might be represented by figure 46, *a*. Coarse-grained sediments brought by streams from the nearby landmass were deposited as an alluvial fan on an emerged shelf, while the finer-grained clays were carried north and south. The coals that occur below Coal IIIA to the north and south of the delta suggest that for periods of time these areas were not completely submerged but were paludal. Thus, it would appear that most of the area under consideration was predominantly continental and was probably a subsiding shelf area (see p. 21). Sediments were deposited occasionally, they were often weathered (underclay), and swamps occasionally characterized the non-deltaic portions. The area was undoubtedly complex. Sandstone, siltstone, shale, marine limestone (Core 77), underclay, and coal are all found in the ten feet below Coal IIIA at one location or another (see fig. 45, *a*).

The competence of the streams decreased gradually as the source area was eroded or subsided. The streams carried finer sediments into the area, resulting in an upward

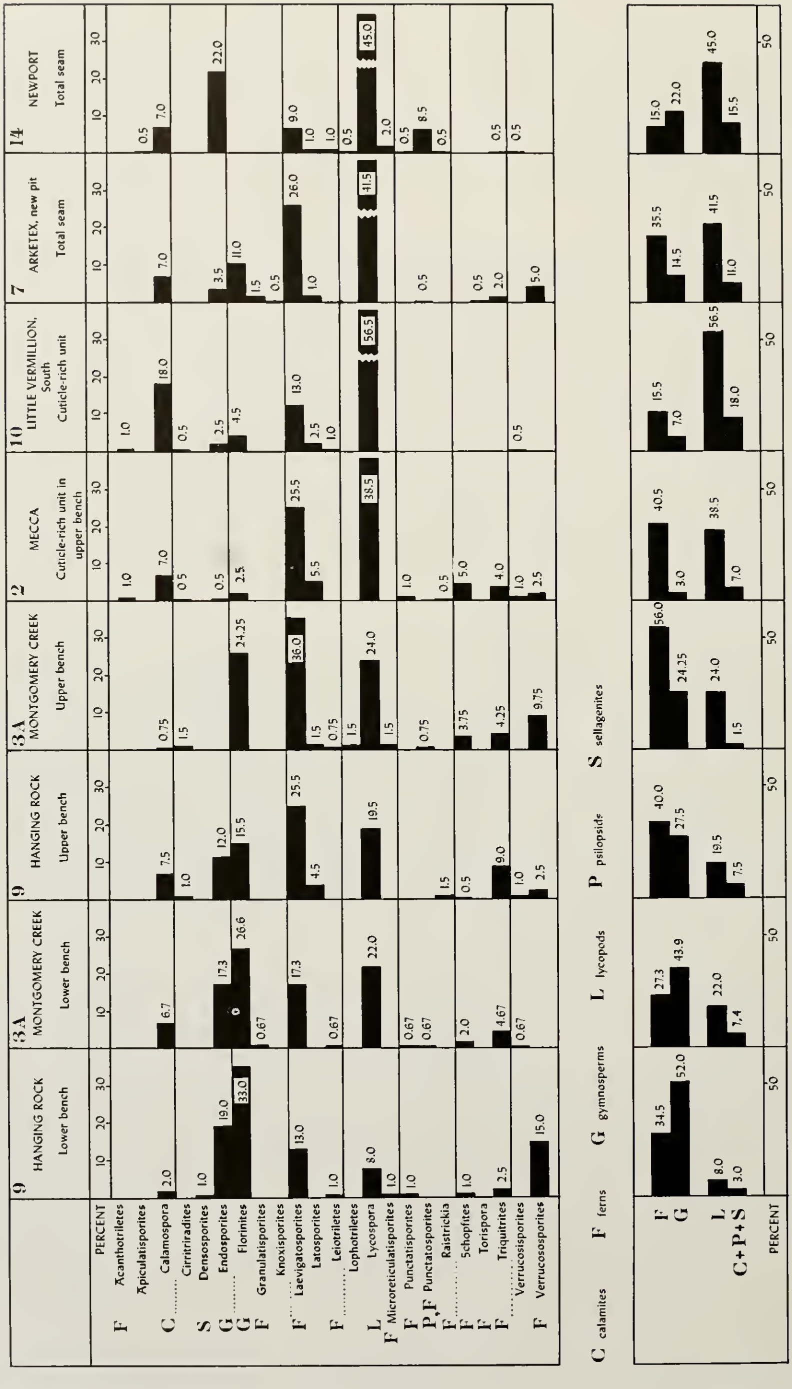


FIG. 44. Spore analysis of Coal IIIA: Above (*a*), comparative abundance of spore genera; below (*b*), comparative abundance of spore types.

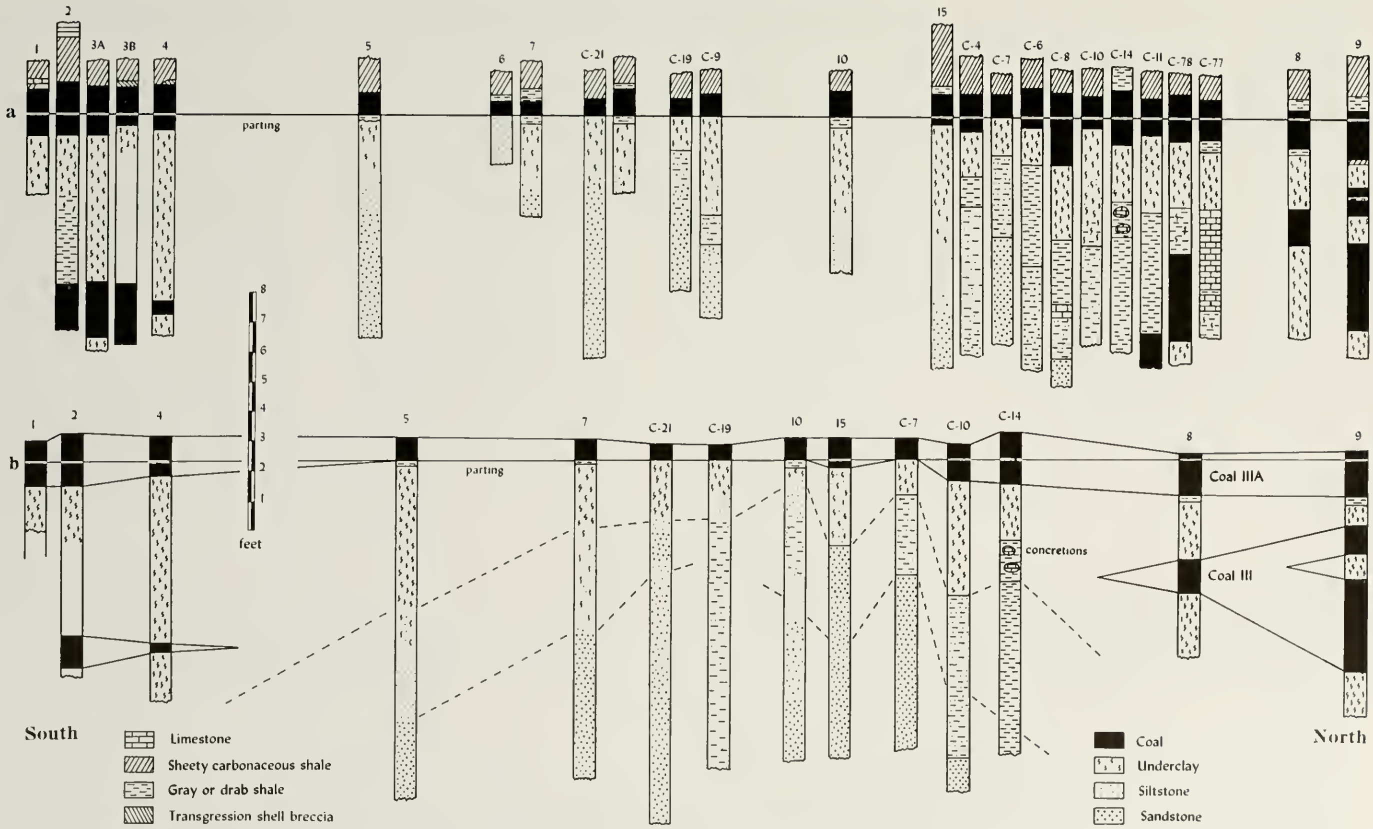

a
1
2
3A
3B
4
5
6
7
C-21
C-19
C-9
10
15
C-4
C-7
C-6
C-8
C-10
C-14
C-11
C-78
C-77
8
9
parting
8
7
6
5
4
3
2
1
feet
b
1
2
4
5
7
C-21
C-19
10
15
C-7
C-10
C-14
8
9
parting
Coal IIIA
concretions
Coal III
South
North
Limestone
Sheety carbonaceous shale
Gray or drab shale
Transgression shell breccia
Coal
Underclay
Siltstone
Sandstone

FIG. 45. (*a*) Stratigraphic columns of Coal IIIA, Coal III, and associated sediments at localities shown in figure 43. (*b*) Stratigraphic columns of Coal IIIA, Coal III, and associated sediments along line A–B of figure 43.

decrease in grain size in the deltaic deposits. These exposed sediments were constantly subjected to weathering, probably under a plant cover, and they formed an extensive muddy flat. The formerly complex area appears to have been essentially leveled by local weathering, erosion, slumping, and sedimentary infill. Thus, the stage was set for deposition of Coal IIIA.

Thick deposits of peat, the precursor of coal, can be formed only when certain critical conditions exist. The plant parts are preserved in standing water which is toxic to aerobic bacteria and other decay-causing organisms. This standing water must not, however, be so deep as to preclude plant growth. A swamp that is being inundated or is subsiding at a rate that allows water to remain at or near the top of the accumulating peat fulfills the critical requirements. The relative subsidence of the landmass, suggested as a reason for the decreased stream competence, probably resulted in the formation of the Coal IIIA swamp. Inflowing fresh water was dammed by the consequent rise in sea level and served as the principal cause of swampy conditions on the previously mentioned flats.

Figure 46, *b*, shows the suggested geographic setting as peat began to form. Coal IIIA began to form first in the northernmost part of the area (Hanging Rock location). The lower bench is thickest there and thins progressively upward onto the deltaic deposits. The coals below Coal IIIA in this column probably formed because normally this locality was lower and therefore more often subject to flooding, with consequent swamp formation.

Detailed analyses of the coal can now be used to shed light on the sequential development of the peat throughout the area. Figure 47 shows diagrammatically the composition of the coal columns. These data were obtained principally from binocular microscope examinations of the polished columns. Most of the coal in each column is bright and finely banded. Layers or benches of less typical coal types, however, can be discerned by such examinations.

The unusual layers (dull attritus layers and cuticularized leaf layers) were undoubtedly formed in conditions which differed from those that resulted in clarain (bright, banded coal) accumulation. It is immediately obvious that these unusual conditions were not widespread. For instance, it is difficult if not impossible to correlate any of the dull layers. The same is true of the leaf layers. Thus, it can be concluded that local irregularities in the swamp environment were responsible for the formation of the atypical layers. However, the consistent recurrence of conditions leading to formation of dull attritus layers in the lower bench suggests that the lower bench depositional period was characterized by normal peat-forming stages alternating with stages in which dull attritus accumulated. The upper bench was formed in a normal, peat-forming environment in which occasional abnormal conditions caused cuticularized-leaf accumulation.

Thin sections of selected samples were examined to assess the conditions that led to the formation of the various coal types. Thin sections of the complete columns of samples 3A and 6 were examined. Selected thin sections of sample 3B and sample 2 were also examined.

Peat is an accumulation of plant parts. The great diversity of potential source materials in any ecological community makes attempts to characterize the microscopic appearance of a thin section of coal difficult. Peat can be analyzed by picking apart the various plant parts, but in coal these plant parts have been bound together by the compression which forms coal from the peat. It is possible to recognize individual plant parts in a thin section of coal; however, the examiner is limited to a two-dimensional picture. If one were to examine a handful of peat from a present-day bog, he would more than likely find that it is composed of recognizable sticks, twigs, and leaves embedded in an indistinguishable,

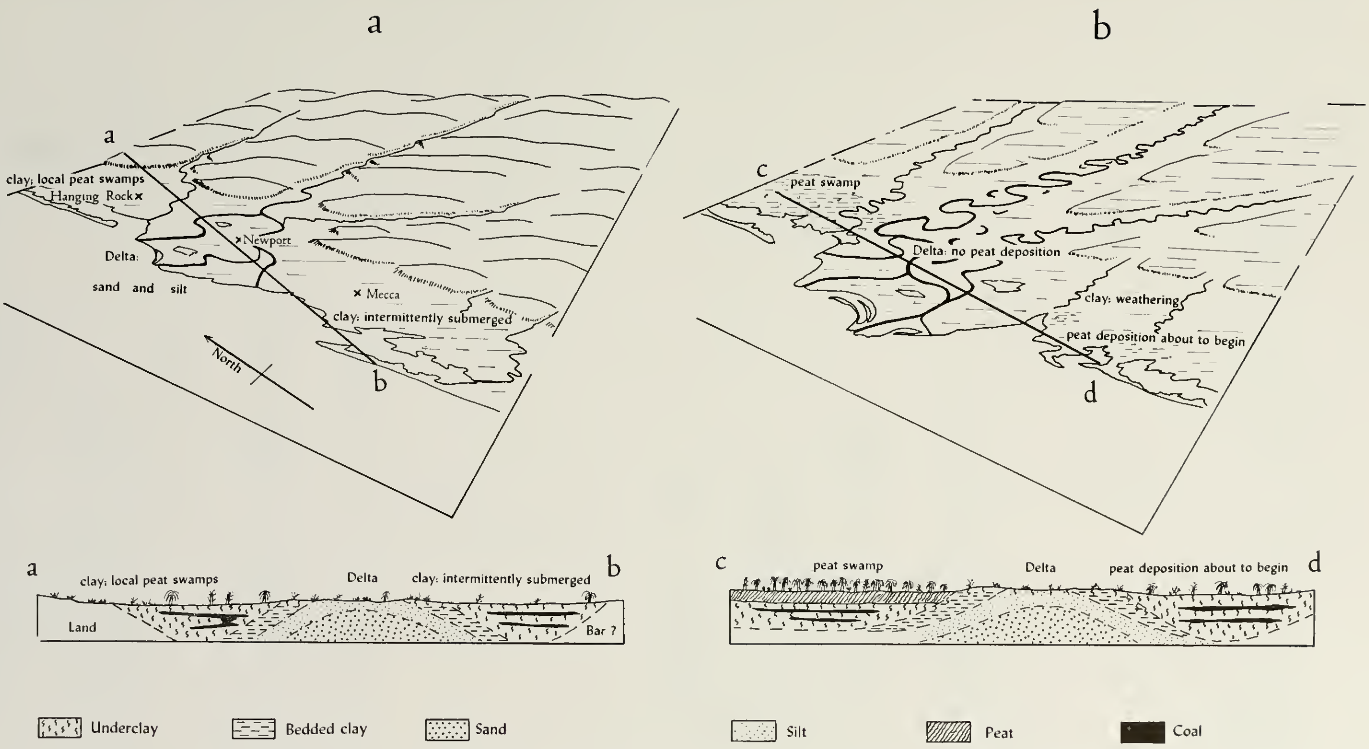

a
b
a
clay; local peat swamps
Hanging Rock ×
× Newport
Delta:
sand and silt
× Mecca
clay: intermittently submerged
North
b
c
peat swamp
Delta: no peat deposition
clay: weathering
peat deposition about to begin
d
a
clay; local peat swamps
Delta
clay: intermittently submerged
b
Land
Bar ?
c
peat swamp
Delta
peat deposition about to begin
d
Underclay
Bedded clay
Sand
Silt
Peat
Coal

FIG. 46. (*a*) Paleogeography in region from Mecca to Hanging Rock, before deposition of Coal IIIA. (*b*) Paleogeography of same region during beginning of deposition of Coal IIIA. Beneath each geographic sketch, a cross section along the lines a–b and c–d, respectively, shows the succession of sedimentary rocks beneath the surface, based on the stratigraphic columns in figure 45, *b*.

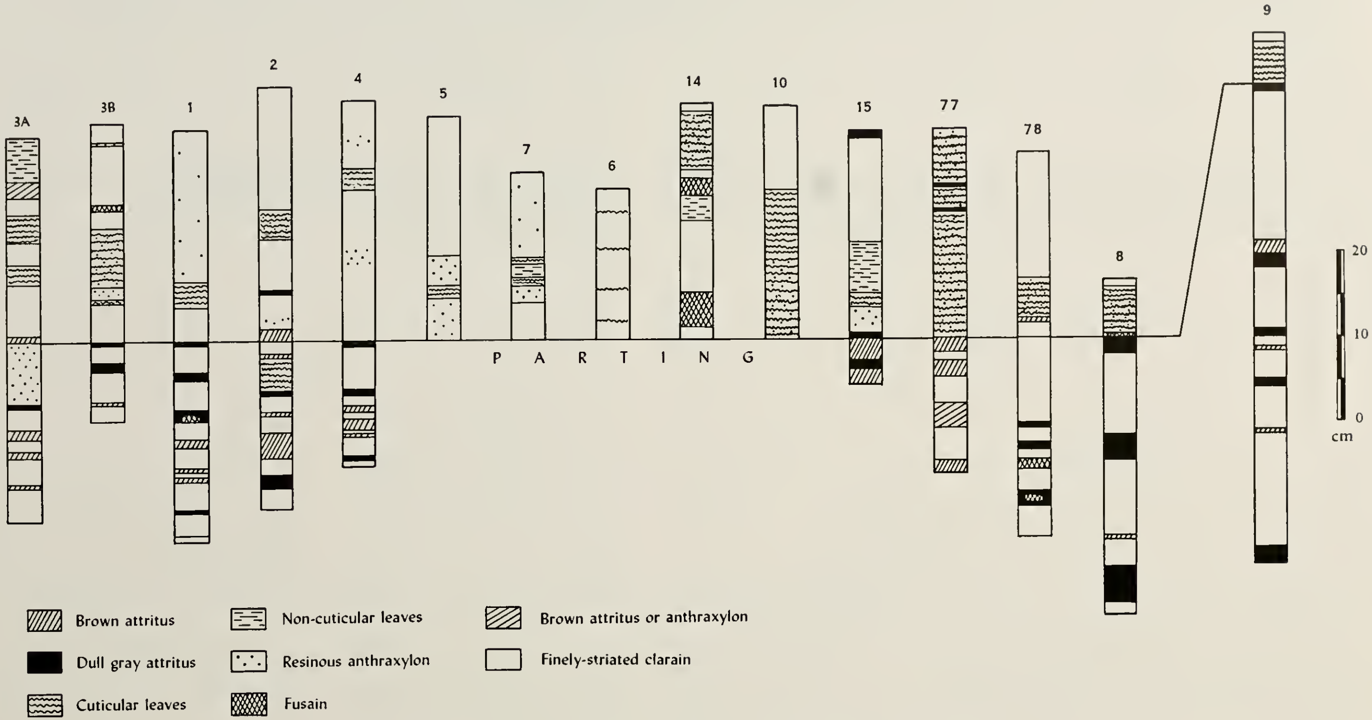


FIG. 47. Composition of Coal IIIA; localities as in figure 43.

very fine, organic ooze. The coalified remains of twigs, sticks, bark, and some leaves are the bright, glassy, conchoidally fracturing, horizontal bands which give most coal its banded or striated texture. These bands are called anthraxylon. The dispersed, finely granular matrix in which anthraxylon is embedded is called attritus. Attritus may appear dull or bright on polished surface. The appearance is controlled by the relative amounts of the various contributing substances. These substances are highly variable, but spore exines, finely macerated wood and other cell-wall components, very small pieces of fusain, and mineral matter generally constitute most attritus. Fusain refers to woody material that was converted to charcoal before deposition. It is seldom altered much during coalification, and therefore it is readily recognized.

It is very difficult to assign specific origins to various kinds of anthraxylon because the cell structure (normally used to identify wood) has been almost obliterated by coalification. However, some anthraxylon retains sufficient cell structure to indicate the type of plant from which it was derived. A clue to the environment can be obtained from this information. The texture and composition of the attritus can be ascertained. From this the depositional environment can be surmised also.

Figure 48 shows some of the more salient features that could be gained from thin section analyses. The appearance in thin section of the various identifiable constituents is shown in plates 11 through 13. Most of the identifications are based on information given by Thiessen and Sprunk (1941). Most of the anthraxylon cannot be assigned to a plant type. However, it was found that each type of anthraxylon which could be identified occurred within a vertically confined zone. Also, there were certain zones that could be characterized by the composition of the attritus. These zones are marked in figure 48.

As was suggested by evidence derived from the underlying sediments, the coal of sample 3A at Montgomery Creek began as a relatively dry deposit. The recognizable anthraxylon in the lowest zone is predominantly of gymnospermous origin (see pl. 11, B). Gymnosperms are generally considered to be one of the "drier" plant types. The three dull attritus layers appear to have resulted from oxidation and decay of the contributing plant parts. Only the more decay-resistant elements are preserved in these layers (see pl. 11, C). These elements are pieces of fusain and the highly lignified cell walls of sclerotic stone-cells. Thus it would appear that the beginning stage of peat deposition was characterized by a water level that did not constantly cover the peat and retard decay. Gymnosperms appeared best able to flourish in this environment.

Zone 2 is characterized by unusual, and, to me, unidentifiable anthraxylon (see pl. 12, A). An increase in the amount of "wet" attritus (spore exines in coalified organic ooze, i.e., vitrinite cf. collinite; pl. 12, B) suggests that the swamp was becoming wetter. Zone 3 contains remains of resinous anthraxylon (pl. 12, C) from plants that established themselves before the lycopods of Zone 4. The resinous anthraxylon probably is derived from cycadophytes. The lycopods (pl. 13, A) apparently represent a flora that could tolerate deep water conditions (1 to 2 feet?).

The parting was deposited apparently by a major flood or series of floods. Whether all plants were obliterated is uncertain. No plant remains are found in the parting. At location 3A, Montgomery Creek, the parting is found in the column, but it pinches out several feet away. Islands of vegetation may have existed during the deep-water parting phase.

Zone 5, immediately above the parting, is characterized by untextured anthraxylon in "wet" attritus. The effects of the high-water flooding conditions were still in evidence.

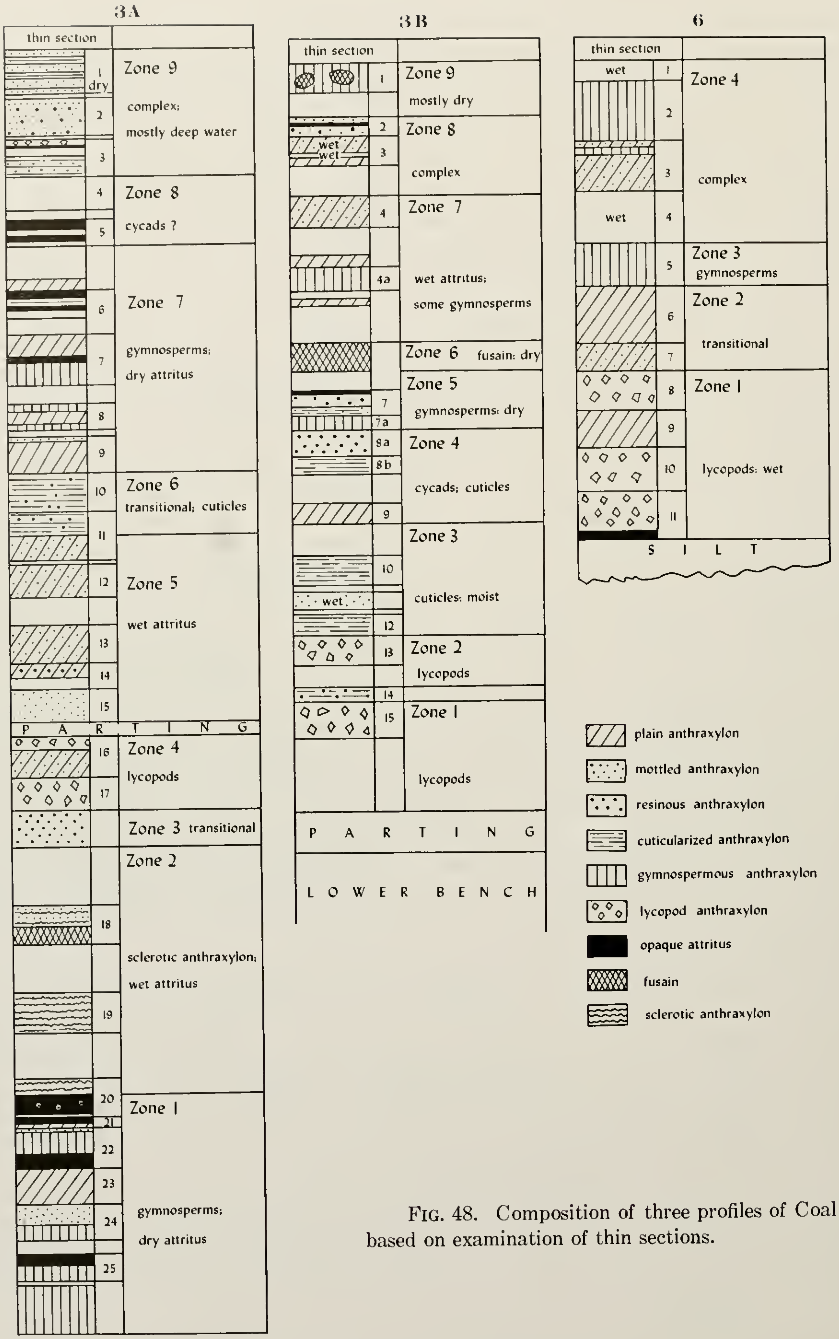
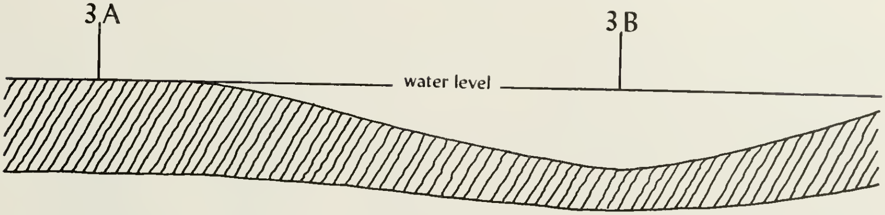
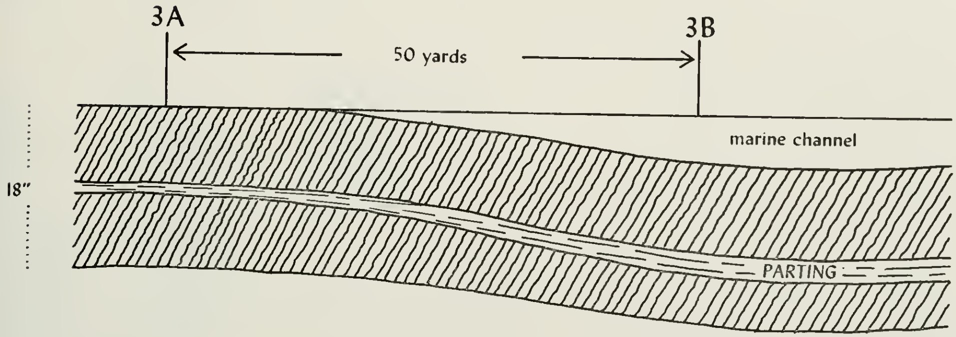

3A
thin section
1 dry
2
3
Zone 9
complex; mostly deep water
4
5
Zone 8
cycads ?
6
7
8
9
Zone 7
gymnosperms; dry attritus
10
11
Zone 6
transitional; cuticles
12
13
14
15
Zone 5
wet attritus
P A R T I N G
16
17
Zone 4
lycopods
Zone 3 transitional
18
19
Zone 2
sclerotic anthraxylon; wet attritus
20
21
22
23
24
25
Zone 1
gymnosperms; dry attritus
3B
thin section
1
Zone 9
mostly dry
2
wet
wet
3
Zone 8
complex
4
4a
Zone 7
wet attritus; some gymnosperms
Zone 6 fusain: dry
7
7a
Zone 5
gymnosperms: dry
8a
8b
9
Zone 4
cycads; cuticles
10
wet
11
12
Zone 3
cuticles: moist
13
Zone 2
lycopods
14
15
Zone 1
lycopods
P A R T I N G
L O W E R B E N C H
6
thin section
wet
1
2
3
wet
4
Zone 4
complex
5
Zone 3
gymnosperms
6
7
Zone 2
transitional
8
9
10
11
Zone 1
lycopods: wet
S I L T
plain anthraxylon
mottled anthraxylon
resinous anthraxylon
cuticularized anthraxylon
gymnospermous anthraxylon
lycopod anthraxylon
opaque attritus
fusain
sclerotic anthraxylon

FIG. 48. Composition of three profiles of Coal IIIA, based on examination of thin sections.



a, before deposition of parting



b, before deposition of sheety black shale

FIG. 49. Stages in the accumulation of Coal IIIA at Montgomery Creek. (*a*) Prior to deposition of clay parting, less peat accumulated beneath marine channel than lateral to it. (*b*) Clay parting is thicker beneath marine channel than lateral to it; channel persisted after accumulation of peat.

However, Zone 6 contains considerable resinous anthraxylon like that found in the transitional Zone 3 of the lower bench. Unlike Zone 3, however, Zone 6 contains the remains of cuticularized leaves (pl. 11, A). Thus, it seems probable that the swamp was once again drying out.

As it did, the remaining water became extremely toxic due to a greater concentration of decay products. Thus what amounted to drought conditions existed. Water was present, but it was too toxic for the plants to use. The floral community took on a xerophytic aspect, which is best exemplified by abnormal cuticle production. Cuticle tended to decrease the loss of the water that the plants did absorb. Zone 7 contains considerable gymnospermous remains. This suggests that the swamp again reverted to an almost dry area. There are several thin layers of dull attritus in the upper half of Zone 7. In many respects, these dull layers are similar to the dull layers in Zone 1, except that they are thinner.

Zones 8 and 9 contain both dry and wet elements. These two upper zones are similar in some respects (resinous anthraxylon, cuticularized anthraxylon) to the two transition Zones 6 and 3. Zones 8 and 9 are transitional between the dry Zone 7 and the black shale phase that ended peat formation.

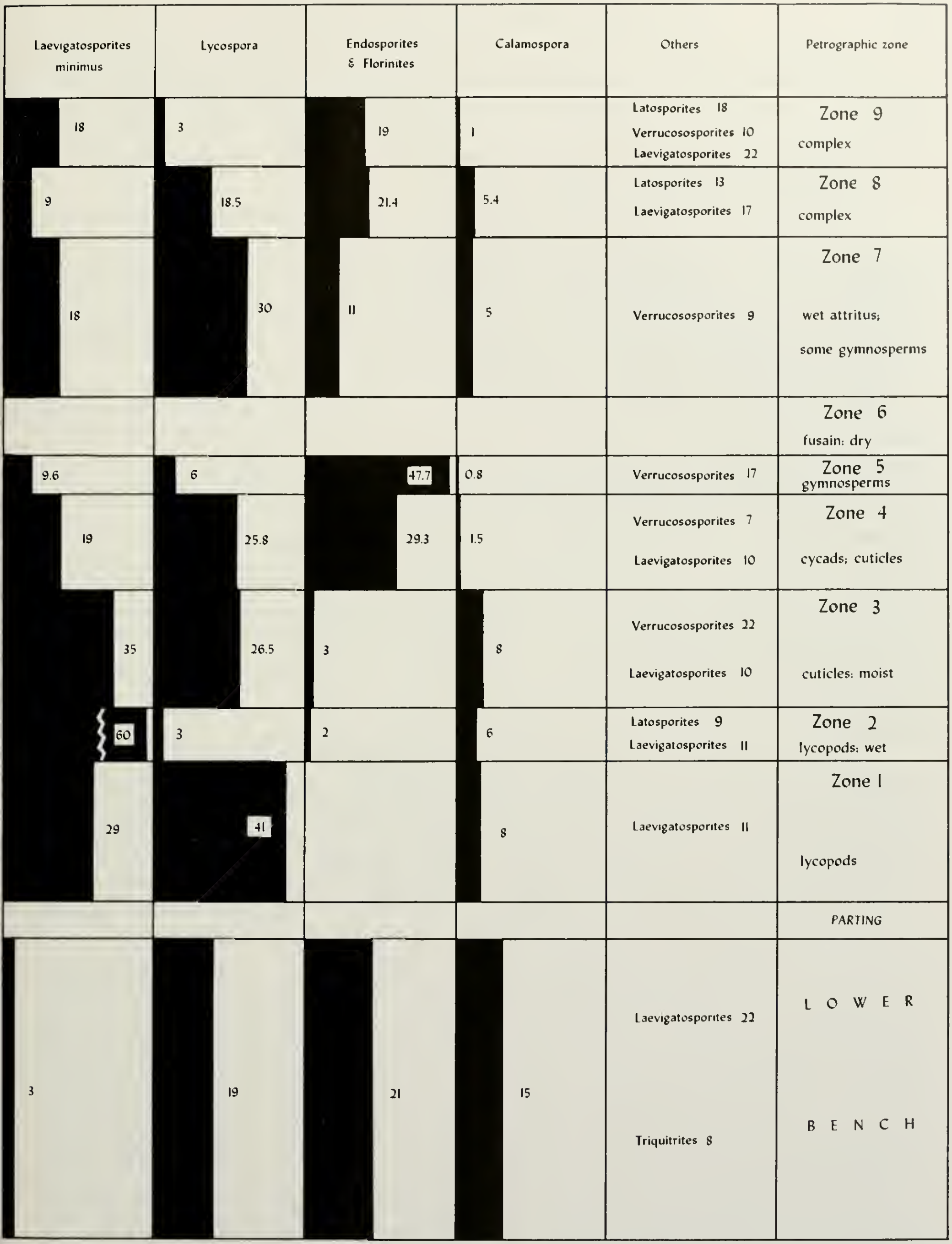
Column 3B at Montgomery Creek was studied in somewhat less detail. The lower bench is similar to the lower bench of column 3A except that 3B is thinner. The presence of a marine channel clod above column 3B suggests that the area was lower after peat deposition and served as a channel during marine transgression. This condition was probably an inheritance from pre-peat topography. Figure 49 suggests how this may have developed. The lower bench, deposited in a trough, is thinner because either the peat was washed away by flowing water or plants did not grow in the deeper water and the source material was blown or washed there. The parting is about 3 cm. thick at 3B, but at 3A it is less than one cm. thick. This is consistent with the idea that 3B was lower than 3A; while peat accumulated at 3A, mineral detritus was deposited in the channel at 3B. The upper bench of column 3B contains much more pyrite than in 3A (cf. pl. 13, B). This fact suggests a more reducing environment, under deeper, stagnant, less oxygenated water than that found at 3A. The coal composition is also consistent with this hypothesis. Zones 1 and 2 (immediately above the parting) in sample 3B contain lycopod remains, but Zone 5 above the parting in sample 3A contains unrecognizable remains, probably of ferns or similar small plants. Lycopods were probably much more tolerant of deeper water (maybe only 6 inches deeper) such as is suggested for 3B than were the smaller plants.

Zone 3 in sample 3B contains considerable cuticularized anthraxylon and probably correlates with Zone 6 in sample 3A. Gymnospermous leaves in thin section 7A (Zone 5, column 3B) correspond to those in Zone 7 of 3A. In 3B, as in 3A, the upper part of the seam shows a complex of dry and wet features.

Figure 50 depicts the distribution, as determined by G. K. Guennel, of spore types in the zones of sample 3B. Each of the zones was macerated and analyzed as a separate sample. These data further substantiate the conclusions obtained from the thin-section studies. The lower bench contains a complex flora which, as can be seen from the thin-section studies of sample 3A (and it must be remembered that many of the spores found in 3B probably blew in from the 3A location), is divisible into vertically distinct zones. Had we divided the lower bench of 3B into incremental samples for spore study, we probably would have found gymnosperms at the bottom, calamites (*Calamospora*) in the middle, and lycopods at the top.

We may now draw further conclusions from the spore distribution in the upper bench at location 3B. As was suggested by the petrographic study, the upper bench began to accumulate in a wet environment inhabited principally by lycopods. As the swamp began to dry, *Laevigatosporites*-bearing plants—medullosans or cycadophytes are suggested by the resinous nature of the anthraxylon—established themselves. These in turn, gave way to an increasing number of gymnosperms. Unquestionably, the fusain in Zone 6 at site 3B represents an accumulation of highly oxidized plant remains which resulted from complete exposure (and possibly from burning) of the peat. After this fusain deposition the water was again deeper (lycopods) and then became characterized by a complex flora which included a fair proportion of gymnosperms.

The petrographic composition of column 6 is shown in figure 48. The flood that formed the parting deposited clayey silt here, as opposed to clay elsewhere. As the flooding conditions receded, the water level decreased to a depth which allowed plants to root. Lycopods then established themselves on the delta as well as elsewhere. This column began with the accumulation of lycopods which eventually gave way to a complex flora that included gymnosperms. Although there are no layers of concentrated cuticularized leaves, such leaves do occur scattered throughout the column.



Laevigatosporites minimus	Lycospora	Endosporites & Florinites	Calamospora	Others	Petrographic zone
18	3	19	1	Latosporites 18 Verrucososporites 10 Laevigatosporites 22	Zone 9 complex
9	18.5	21.4	5.4	Latosporites 13 Laevigatosporites 17	Zone 8 complex
18	30	11	5	Verrucososporites 9	Zone 7 wet attritus; some gymnosperms
					Zone 6 fusain: dry
9.6	6	47.7	0.8	Verrucososporites 17	Zone 5 gymnosperms
19	25.8	29.3	1.5	Verrucososporites 7 Laevigatosporites 10	Zone 4 cycads; cuticles
35	26.5	3	8	Verrucososporites 22 Laevigatosporites 10	Zone 3 cuticles: moist
60	3	2	6	Latosporites 9 Laevigatosporites 11	Zone 2 lycopods: wet
29	41		8	Laevigatosporites 11	Zone 1 lycopods
					PARTING
3	19	21	15	Laevigatosporites 22 Triquitrites 8	LOWER BENCH

FIG. 50. Spore content in zones of Coal IIIA beneath marine channel at Montgomery Creek (sample 3B, analyzed by G. K. Guennel).

Examination of the Mecca column (2) indicates that it was formed in a wetter environment than the Montgomery Creek column 3A. The layer of cuticularized leaves and resinous anthraxylon in the lower bench appears significant. These features are normally found in the upper bench of Coal IIIA, which bench is considered to have been formed in a wetter environment. Thus, it is suggested that the lower bench at Mecca was formed under wetter conditions than prevailed elsewhere.

The Mecca column contains abundant pyrite in the form of small crystals (pl. 13, B). The Montgomery Creek sample 3B, interpreted as a deeper water deposit, also contains abundant pyrite. The abundant "wet" attritus which also occurs in the upper part of the Mecca column is indicative of deep-water conditions. This material (shown in pl. 12, B and pl. 13, B) probably originated as an organic ooze which precipitated from the water cover. It is common knowledge that the water in many swamps contains abundant suspended organic matter. Much of this material is incorporated into peat.

Thin sections of the coal in the Logan Quarry were also studied. This coal lies about 65 feet below Coal IIIA. It is thin (3–4 inches) and very dull. The dullness is not caused by drying and oxidation as is typical of the dull attritus in the Coal IIIA column; rather, it is due to an abundance of detrital mineral matter. Plate 13, C, shows the typical appearance of this coal. The abundant detrital mineral matter indicates that this area of the swamp was almost constantly receiving a flow of detrital particles. Therefore, moving water is indicated. The abundant pyrite, however, suggests highly reducing conditions below the water-peat interface. The presence of abundant pyrite in a coal which was undoubtedly formed below moving water tends to substantiate the conclusion expressed previously that the abundant pyrite in samples 3B and 2 indicates deeper-water origins for them than for sample 3A.

Summary

Fifteen columns of Coal IIIA could be correlated on the basis of their petrographic composition and their spore contents. Once this correlation was established, the relationships exhibited by the sediments underlying the coal became evident. The area between Hanging Rock and Montgomery Creek was apparently fairly complex before deposition of Coal IIIA began. The center of this area was an alluvial delta or fan. Underclay and coal formed on either side of the delta. Sedimentary infilling leveled much of the area. As the transporting streams lost competence, weathering and slumping leveled the area further. Underclay formed throughout the area by weathering and leaching.

Damming of inflowing fresh water resulted in the formation of a swamp throughout the region. Peat began to accumulate first at Hanging Rock, and then in the Mecca–Montgomery Creek area. This period of peat deposition was characterized by occasional periods of dryness during which the peat was oxidized and decomposed. Due to subsidence, the swamp gradually became wetter until finally peat accumulation all but ceased and a clay parting was deposited. Following this stage of development, the swamp began to dry out. It would appear that before the peat ever became completely exposed, the area again subsided and the sea inundated the region. The black-shale phase of deposition commenced.

Local topographic irregularities in the region resulted in the formation of different types of coal in the various columns. These irregularities appear to have persisted throughout the history of the swamp and they are reflected in the lateral variations which characterize the black shale.

IV. THE HISTORY OF THE MECCA AND LOGAN TRANSGRESSIONS; AN ATTEMPT AT SYNTHESIS[1]

The study of the Mecca and Logan Quarry shales as set forth in the body of this paper is based on multiple lines of evidence, each one of which is amenable to a variety of interpretations. Most of these interpretations, however, are in direct conflict with some other evidence and may thus be safely ignored. Because of the notable complexity of the problem, the large amount of evidence, and the necessity for detailed interpretations that are mutually compatible as well as satisfying all of the presently available evidence, an attempt at an overall synthesis seems in order.

A. THE HISTORIC BACKGROUND OF THE MECCA AND LOGAN TRANSGRESSIONS

1. *Cyclic Deposition Between Minshall and Velpen Limestones*

The portion of the stratigraphic column considered in this paper, namely, from the Minshall to the Velpen limestones, contains five cycles of deposition (cyclothems) in which the terrestrial phases, probably because of erosional gaps, appear very much reduced. In most cases periods of coal deposition were followed by marine transgressions, but two coal seams (Coals II and III) appear to have been formed in the wake of marine regressions. The lower four cyclothems are closely spaced and were probably of relatively short duration. This was a period of rapid change along the margins of the epicontinental sea and the repeated transgressions of marine waters over the marginal coal swamps were probably of limited areal consequence. At the time of the formation of the Lower Lodi peat, however, a transgression of much broader scope occurred, resulting in the deposition of a thick profile of drab shales that ended with the establishment of a new land surface on which the peat of Coal III was laid down. The thin sequence between Coals III and IIIA was probably formed under non-marine conditions, as it consists of stream-borne sands to the south and fine shale farther north.

In contrast to the earlier cyclothems in which especially the terrestrial phases of the cycles show notable regional variations, Coal IIIA and its Mecca Quarry shale roof are much more uniform, and they extend over an extremely wide geographic range. Throughout the observed stratigraphic interval the cyclothems show remarkable similarities in the sequence of beds, so much so that the identification of a given suite of sediments, seen in a limited outcrop, may present extreme difficulties. While the cyclothems as a whole show many similarities, the beds reflecting the initial transgression histories are even more strikingly repetitive. Characteristically, these sediments—focal point of interest in the present study—consist of a series (usually 8 in number) of alternating gray and black sheety shale levels that form the roofs of the coal seams. These sheety shales reflect the transitory, transitional environments that led to the establishment of typically marine conditions on earlier land surfaces. The similarities between these shales, both areally and in successive cyclothems, go far beyond the obvious outcrop resemblance. In terms of depositional character, microscopic structure and basic composition, as well as in the peculiarities of fossil content, these shale sequences are virtually identical. There would appear to be little doubt that the shales reflect repeated similar histories of origin.

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[1] For the sake of readability, constant page reference to evidence and discussions in the body of this paper has been omitted.

These sheety shales are characteristic elements in the cyclical rhythm of deposition along the fringe of the Illinois Basin, and contain a wealth of fascinating biostratonomic evidence. Hence they are not only of interest in the depositional and ecological histories of the cyclical phases that they represent but are also of notable significance in the interpretation of some of the broader aspects of the history of the Illinois basin to which they belong.

2. *The Broad Paleophysiographic Setting of the Outcrop Belt*

During the time span between Minshall and Velpen limestones the Illinois Basin appears to have been filled, for much of the time, by an epicontinental sea. In a general way the Pennsylvanian outcrop belt in western Indiana marks the eastern fringe of the basin. The geographic location of the shore zone, however, underwent continuous change; it migrated back and forth in an east-west direction, remaining approximately parallel to the outcrop belt of the sediments. Because of the regional dip of the sediments toward the southwest, the outcrop belt of any specific horizon (in the limited area of our study) is a rather narrow band approximately parallel to the ancient shore zone. Hence it is not possible to study the amplitude of the back-and-forth movement in any given stratigraphic cycle, or the full physiographic differentiation from the shore to the hinterland. Instead, each stratigraphic level reflects but a narrow physiographic zone (about 5 miles in width) parallel to the margin of the basin, and the relationship of this zone to the shore line is to be determined in each case (fig. 51).

The Mecca Quarry shale, along its outcrop belt, was deposited on a low coastal plain, immediately adjacent to an extremely irregular pre-transgression shore line of the epicontinental sea. Landward it does not extend beyond physiographic features that are intimately associated with the coastline. The outcrop belt of the Logan Quarry shale lies farther landward, along a physiographic zone characterized by coastal marshes and bodies of fresh water. These two zones appear to be adjacent to one another and there is at least some overlap between them.

Although we have much less evidence for the remaining black shale horizons between the Minshall and Velpen limestones, there appears to be little doubt that all of them reflect physiographic zones similar to those of the Mecca and Logan Quarry shales.

3. *The Pre-Transgression Physiography of the Mecca and Logan Quarry Shales*

While it is impossible to draw accurate maps of the pre-transgression surfaces of either the Mecca or the Logan Quarry shales (because of the scarcity of outcrops) the evidence permits the description, in principle, of the major physiographic features.

The pre-transgression surface of the Mecca Quarry shale was a rather flat plain, practically at sea level, on which a fair quantity of peat had been deposited. This coastal plain was uniformly flat, except for occasional slight elevations and depressions. The latter were drained by small bayous that connected seaward with inlets of various sizes. These features are represented by the channel clods, which are typically seen only in the westernmost outcrops. The channel clod at Pit 3, West Montezuma, contains evidence of a massive bank, about two feet thick, of productids preserved in such a way as to indicate a bioherm. Hence there must have been fairly clear marine waters near this place. At the Arketex pit, farther north, the coal overlies a former delta, and is covered by a variety of light shales, deposited on mud flats associated with the proper margin of the sea. The eastern outcrops are notably more uniform. indicating much less physiographic diversity.

In contrast, the pre-transgression surface of the Logan Quarry shale shows in many places evidence of fresh-water environments. The only one of these that was seen in fresh, horizontal exposure was the lake, pond or oxbow deposit at Garrard Quarry. Elsewhere, similar deposits were noted in vertical, weathered outcrops which did yield the Garrard Quarry fresh-water fauna. It seems highly doubtful, however, that all of them were pond, lake or oxbow deposits as at Garrard Quarry; more likely they are sediments produced in fresh-water marshes. Considering the close geographic proximity to Garrard Quarry the situation at Logan Quarry is astonishingly different. Here the pre-transgression surface was topographically low enough to have been in contact with the marine waters to the west. At a few other points the physiographic setting was similar to that of the Mecca Quarry shale.

4. *Climatic Conditions During the Minshall to Velpen Interval*

We are restricting our discussion of climatic conditions to the stratigraphic interval here studied, because we have no first hand evidence from any other part of the Pennsylvanian profile; we do not mean to imply that this period was necessarily atypical.

The discussion of climatic conditions during Pennsylvanian time has hitherto been based primarily on botanical considerations, the distribution of coal deposits the world over, the occurrence and distribution of modern peat accumulations and the rather delicate relationship between plant growth and decay. The reasoning and the interpretations based on this evidence are clearly summarized by Stutzer and Noé (1940), who conclude: "We now accept the theory that the climate of the coal age was warm, moist, and uniform but not tropical."

Our own evidence relating to this topic is largely independent of the evidence so far marshalled for the discussion. We have been able to establish the time involved in the deposition of the Mecca Quarry shale: approximately four years. During this time, four periods of low water alternating with four periods of high water may be distinguished. There appears to be little doubt that these dry and wet periods reflect seasonal cycles similar to those presently characteristic of tropical savanna climates with wet and dry seasons, and humid mesothermal, subtropical climates with winter drouth and summer rain (terminology following Trewartha, 1943). In both of these climates the range of mean monthly temperatures is rather small; there is a conspicuous dry period during the winter months while a great deal of precipitation is recorded during the summer.[1]

This conclusion does not wholly agree with previous interpretations of the coal age climate. Potonié (1920) has argued for a tropical rain forest climate, Frech (1912) and Dannenberg (1909) for a moderate marine forest climate such as exists in New Zealand, southern Chile, or England. Both of these climate types are characterized by little fluctuation in the mean monthly temperatures and by more or less even distribution of rainfall during the year. White and Thiessen (1913) stress the uniformity of the Pennsylvanian climate both locally and all over the world. We agree that the climate was warm, with relatively little seasonal temperature fluctuation, but not uniformly wet throughout the year; rather there were marked seasonal changes in the amount of precipitation.

[1] It was not possible to determine during what part of the year the dry periods occurred.

It may be objected that this conclusion is based on evidence representing a time span of only four years which, admittedly, is woefully inadequate for the characterization of the climate of a given area, and that the observed phenomenon merely reflects a transient period of unusual weather conditions, correlated, perhaps, with the changes that are responsible for the transgression.

This possibility cannot be ruled out completely though it seems rather unlikely for the following reasons: in the region of our study all transgressive sheety shales (irrespective of stratigraphic level) show the characteristic alternation of black and gray (or hard black and soft black) levels seen in the Mecca Quarry shale and there is good reason to believe that the causative factors are essentially the same in all cases. The seasonal alternation between dry and wet periods is thus not a phenomenon peculiar to the Mecca Quarry shale but a regular feature of all transgressive sheety shales within the scope of our observations. Furthermore, if these shales had been deposited during abnormal periods of unusually extreme weather, it is difficult to understand why this should have resulted, repeatedly, in the observed cyclical pattern during the initial few years of each transgression.

It is much more likely that the type of climate indicated by the sheety shales was the prevailing climate during the Minshall to Velpen period in the domain of the Illinois Basin. The sheety transgressive shales, because of the particular conditions under which they were formed, are the only sediments of the profile so severely affected by the cyclical character of the climate as to have preserved such evidence.

The present interpretation of the climate does not conflict with the evidence presented by previous writers. Thin sections of shale vertical to bedding show clearly that even the blackest levels contain grayer micro-bands, indicating that the dry periods were not wholly lacking in rainfall; and occasional darker micro-bands in the gray levels signify short episodes with little precipitation during the wet periods. The view that seasonal drying of the peat accumulations would probably have resulted in their total destruction, or would have prevented the formation of peat altogether, seems in itself reasonable, but does not take into account the fact that most of the peat accumulated along the low coastal plains where the groundwater table must have been high enough to keep the peat wet even during dry seasons. Even so, fusain and dull attritus levels within the coals show that the peat surface did occasionally dry out.

B. THE HISTORIES AND CONSEQUENCES OF TWO TRANSGRESSIONS

The following account will depict the histories of the Mecca and Logan transgressions primarily in terms of the changes in the physical environments.

1. *Changes in the Relative Stability of the Environments*

The coastal plain environments that existed before the onset of the transgressions appear to have been fairly stable for some time. The formation of peat, a near-uniformly organic sediment, indicates the relative stability. As such the peat lacks evidence of obvious seasonal differences.[1] Apparently the peat deposition phase of the cyclothem represented a period in which stream competence was low and flooding occurred very rarely (as evidenced by occasional partings in the coal seams).

The slow but probably continuous process of sinking of the basin became almost imperceptible. These episodes of relative stability lasted for different intervals of time, depending on the interpretation of rates of peat accumulation and the thickness of the coal seam at a given horizon. During Coal IIIA time it lasted much longer than at the time of deposition of the Logan Quarry coal.

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[1] It appears conceivable, however, that more careful investigation, especially of poor-grade coals and sediments intermediate between coal and carbonaceous shale, might yield such information.

The onset of the transgressions produced an extremely sharp depositional change. Quite clearly this was not a gradual seeping of marine waters over the peat swamp, except along the most landward fringe, but very probably a sudden event accompanied by some amount of violence. In all near-shore locations known to us the first effects of transgressive movements are marine inundations of the coastal plain, resulting in the destruction of the coal swamp vegetation. These inundations left sediment containing quantities of shell debris, and the amounts of sediment decrease with the distance from the open shore or the inlet channels. In our opinion the beginning of the transgressions reflects rather a sudden sustained increase (however slight) in the speed of sinking of the basin. The effect of the initial thrust of the inundation clearly seems to decrease with the distance inland from the shore. For example, at Garrard Quarry the fresh water is very quietly superseded by the quiet marine waters.

2. *The Early Depositional History of the Transgressions*

The early history of the marine transgressions is characterized by the deposition of black and gray sheety shales. Because these shales contain a vast amount of biostratonomic evidence it is possible to reconstruct, in astonishing detail, the sequence of events that took place during the first few years of the transgressions.

The initial thrusts of both the Mecca and Logan transgressions took place some time during the dry season of the respective transgression years. The flooding resulted in the destruction of the coal forest vegetation; at the site of Mecca Quarry the logs of the last trees that lived there were crushed but not completely flattened and were scattered over the peat floor. The flood waters carried relatively little sediment, which was deposited, for the most part, close to shore and in the vicinity of inlet channels. The sediment, rarely more than an inch in thickness, is a dark clod full of fragments of marine invertebrate shells. This marine flooding was not merely the result of a major storm, although a storm or seiche may have accompanied the initial transgression thrust; we must assume that a sudden settling of the basin took place, caused, most likely, by increased tectonic activity. The amount of down-warping was probably slight, measurable perhaps in terms of a few millimeters.[1] Such a slight amount of submergence would, in itself, not have been sufficient to produce complete inundation of the coastal plain. Tectonic movements are, however, generally accompanied by earthquakes and this may have been an important factor at the beginning of the transgression. A series of mild tremors (for which there is no direct evidence) would probably have resulted in the compaction of the loosely packed peat, lowering the level of the coastal plain by a few feet.

Whatever happened during the initial thrust of the transgression, the evidence shows conclusively that the flood waters did not recede completely. The land surface remained under a very shallow cover of water; here and there residual ponds filled slight depressions in the surface of the former coal swamp. During the remainder of the dry season a most remarkable, highly carbonaceous black mud was formed all over the coastal plain.

At the end of the dry season the streams began to carry increasing amounts of water, laden with exceedingly fine-grained clastics. As the volume of fresh water increased, it could no longer run off the coastal plain as readily as in previous years; because the plain was now submerged (and covered by marine water) the incoming fresh water accumulated on the plain faster than it could run off into the main body of the epicontinental sea. As a result there was a marked temporary rise of the water level on the plain, accompanied by the deposition of a fairly thick column of gray mud.

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[1] Sudden, vertical tectonic movements of the order of magnitude of several feet would most probably have resulted in notable faulting and sediment slumping along the margins of the basin, for which there is no evidence whatsoever.

With the onset of the next dry season, the water level of the coastal plain began to fall; the runoff outweighed the volume of incoming fresh water. Once more there was very shallow water all over the plain, and residual ponds in the slight depressions. Again, a layer of black mud was deposited. This alternation of deposition of gray and black muds during wet and dry seasons progressed through four cycles (four years) in both the Mecca and Logan transgressions.[1] The deposition of this alternating sequence of gray and black muds during the initial four years of the marine transgressions in the area studied is contingent on several coinciding factors operating in conjunction only during the earliest phases of the transgressions. One of these is the character of the prevailing climate; another, extremely shallow water at least during the dry season of the year. This is well illustrated by the fact that during the fourth year, when the water cover over the subsiding coastal plain reached greater depth, the alternation between gray and black levels became far less sharply marked than that of the previous three years, and the deposits above these shales exhibit no such alternation. It seems irrational to propose a climatic shift as the reason for these depositional changes, whereas increasing water depth is clearly indicated by the stratigraphic sequence from coal to marine limestone.

While the two factors mentioned explain the development of alternating levels of distinctive muds, the specific characteristics of these sediments were produced by additional factors in the transitional coastal plain environment. The most distinctive of these specific characters are the perfect even-beddedness of these typically sheety shales, the qualitative and quantitative aspects of their microscopic components, and their fossil content.

Explanation of near-perfect sheety deposition of mud in a shallow body of water requires direct or indirect evidence of a mechanism that prevents bottom disturbance by wind and wave action, currents, infauna and plant roots. The absence of currents was deduced from analysis of particle orientation, and there are no signs of infauna or plant roots. Absence of wind and wave action cannot be demonstrated directly.

The microscopic, particulate, organic components of the shale provide indirect evidence. In the absence of currents strong enough to orient such delicate structures as *Listracanthus* spines or water-logged sticks it seems unreasonable to presume that large quantities of plant decomposition products were washed into this environment of deposition from elsewhere. All evidence suggests strongly that this material was of local origin, most likely derived from a floating cover of vegetation of unknown botanical character, probably algal, comparable, at least in principle, to the floating plant communities of modern *flotant* environments. Underneath such modern *flotant* situations the depositional environment is perfectly quiet, entirely undisturbed by wave action; furthermore, a constant rain of decomposing plant debris from the under side of the *flotant* increases the carbon content of the bottom mud. Direct evidence of a floating mat of vegetation in the Mecca and Logan Quarry shales is scant, best documented by the "*flotant* band" (black band) in level J at Logan Quarry, immediately above the carcass of a giant shark.

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[1] Insofar as we have observations for the Holland and IIA transgressions, the situation seems to be identical with those described for the Mecca and Logan transgressions.

The assumption of a profuse growth of floating vegetation over the entire flooded coastal plain during the initial few years of the transgressions not only satisfies the requirements of a perfectly undisturbed environment of deposition and a local source of plant decomposition products, but it seems to be the only interpretation consistent with all of the evidence brought forth in the present study.

This cycle of high and low water during rainy and dry seasons, producing gray and black levels of mud over the former coastal plain, lasted for four years. From the fifth year on, the water cover of the subsiding plain had passed the upper limit of depth at which the yearly dry-wet cycle left its mark on the sediments, and the characteristic transgression fauna was succeeded by a normal marine assemblage.

3. *Regional Differences*

The above account relates the sequence of events during the early phases of the marine transgressions in our area of study. As might be expected, there are some differences in this pattern at different points along the outcrop belt of each sheety shale horizon, due primarily to slight physiographic variations. At West Montezuma, for example, there is only one black sheety shale horizon and the sharp alternation between gray and black levels is absent. This locality lies along the complicated shore line of the epicontinental sea where the water depth except over local high spots must have been slightly greater than farther inland. Residual ponding did occur once at this site, perhaps as a purely local phenomenon within the inlet channel. Otherwise the profile at this place indicates deposition of mud under notably less sheltered conditions than existed on the coastal plain proper. Farther north, at the Arketex clay pit, black sheety shales are rare and the buff to gray shales (varying from point to point within the pit) suggest a delta situation characterized by shifting mud bars and small pools. Farther landward, the typical alternation between shales deposited during wet and dry seasons was formed everywhere, but, depending on the proximity to a drainage channel, there were differences in the amounts of clastics precipitated during the wet periods. Instead of an alternation between soft gray and hard black sheety shales, there may be alternating soft black and hard black sheety shales.

Differences between sheety shale profiles of successive stratigraphic horizons as exemplified by the Logan and Mecca Quarry shales reflect different physiographic settings of the outcrop belts along the ancient coastal plains. The present outcrop belt of the Logan Quarry shale represents deposits that were laid down somewhat farther landward than those of the Mecca Quarry shale; hence there are, in a number of places, fresh-water deposits beneath the transgressive sheety shales.

The site of Logan Quarry proper is somewhat unusual in that it was a topographically low area in pre-transgression time; it may have been a small inlet along the eastern end of a deep embayment which received marine sediments above the underclay (level M). The yearly cycles are very sharply defined and the gray levels are thick, probably indicating that the area served as a bayou during the initial phases of the transgression. All the evidence indicates that Logan was topographically low. The fact that only three yearly cycles are represented at this site agrees with the conclusion (see above) that seasonal cycles have no obvious effect on the sediment except where the water cover is extremely shallow. At Logan the pre-transgression surface was slightly below sea level; hence, deeper water was established in a shorter period of time (three years) than elsewhere along the coastal plain, where the more usual four-year cycle is present.

The relationship of the Logan Quarry site to the pond, lake or oxbow situation at Garrard Quarry is by no means clear.[1] It seems reasonable to conclude, in view of the close proximity of the sites, that the Garrard site was drained by the Logan inlet during pre-transgression time; hence there is no evidence of stagnant conditions at Garrard. The first thrust of the marine transgression submerged the coal swamp at Logan but did not reach to Garrard. The increased water level at Logan stopped the drainage at Garrard, producing stagnant conditions that resulted, during the first dry season, in the curious pyritic humulite (Zone 6), while at Logan level Kb was laid down. During the next wet period the marine waters reached Garrard along with turbid fresh water from the land.

C. THE ECOLOGICAL CONSEQUENCES OF THE TRANSGRESSIONS

While the study of the depositional aspects of the Logan and Mecca transgressions produced many unsuspected results, the ecological aspects of the problem are even more amazing. Seen as a whole the Logan and Mecca transgressions (and others in the Minshall to Velpen interval that have been less carefully analyzed) reflect in each case the destruction of an established terrestrial environment populated by a coal swamp flora and probably fauna (not yet documented by fossils). Because of the extreme instability of the physical environment during the initial few years of this process the establishment of the new biotope followed an erratic and unexpected course.

1. *The Establishment of Transient Environments*

Following the destruction of the coal swamp biotope, a succession of four transient environments developed on the flooded coastal plain. Two strikingly different phases that might be characterized as the *pioneering* and *super-saturation* phases distinguish each of these environments. The pioneering phases coincided with relatively deep water over the plain when organisms from the epicontinental sea invaded the newly created realm; the super-saturation phases followed the pioneering phases during the dry seasons when the water level became precariously low and the organisms were gradually crowded into residual ponds.

The first of these transient environments differed, however, from the three following ones by the fact that the flood waters were those of the epicontinental basin; hence they had the salinity and nutrient content of the sea to the west. This is strikingly correlated with the composition of the pioneer community, which contains as its dominant member the pectinoid *Dunbarella*.

The three transient environments that followed were under the influence of incoming fresh water. The pioneer community reflects this situation in that *Dunbarella* is entirely absent; it is the vertebrates that are the dominant pioneers.

2. *The Initial Marine Transient Environment*

The pioneering phase of this episode is not well documented because the flood waters of the sea carried little sediment other than mud that had accumulated near shore and in inlet channels. The fossils embedded in the resulting clod are broken shells of a variety of animals including the brachiopod *Desmoinesia*, which were not pioneers. All evidence suggests that these fossils are shell debris that had been washed over the coal swamp during the first transgression thrust. Hence the fauna of the transgression shell breccia is not a sample of the pioneer community, but rather of the pre-transgression shore and inlet communities. A good record of the pioneer community developed after the flood waters receded. The water level evidently became so shallow that the free-swimming organisms were gradually concentrated in shallow depressions, where overcrowding occurred.

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[1] In the absence of a time marker in the two profiles we cannot be certain, for example, that the transgressive shales in the two sites were laid down at the same time; a number of interpretations are possible. The above account seems to us, all things considered, the most satisfactory reconstruction of events.

By far the most conspicuous member of this pioneering community is *Dunbarella*, which, in numbers of individuals, far exceeded all other pioneers combined (except perhaps microscopic ones not preserved as fossils). Cephalopods and vertebrates invaded the coastal plain in relatively small numbers, and passive invaders such as inarticulate brachiopods are present but rare. At the site of Mecca Quarry vast numbers of the pioneers died primarily as a result of predation; elsewhere, in situations of a slightly different character, there is evidence that *Dunbarella* may have been destroyed by noxious decomposition products on the bottom, beneath a layer of habitable water (Garrard Quarry, Big Pond Creek, Haworth Creek). At Mecca Quarry and at similar sites elsewhere on the coastal plain the entire *Dunbarella* population was destroyed by the end of the first dry season. The other pioneers were severely reduced in numbers, but there is good evidence that some survived into the following rainy season.

Why did these animals invade an environment whose bottom consisted of a peat bog, barely covered by a thin film of mud (in some places no more than a few millimeters in thickness), and whose water held the same nutrient content as that in which the organisms lived prior to the transgression? It seems possible that the doomed coal swamp fauna (for example, larval insects) provided an immediate source of food, but this is hardly the explanation for the presence of *Dunbarella*. It seems more probable to us that the invasion took place simply because uninhabited new *Lebensraum* was there to be occupied.

3. *The Subsequent Brackish, Transient Environments*

The three transient environments that followed differed from the first one in that they were notably influenced by incoming fresh water. The three episodes are similar but not identical. The effects of the fresh water are most notable during the first and second of these episodes, less so in the third. The pioneer community of these three environments is strikingly different from that of the first; *Dunbarella*, so prominent in the marine transient environment, is typically absent in the new pioneer assemblage. Instead, the dominant pioneers are the vertebrates: a relatively great variety of sharks, a smaller number of species of palaeoniscoid fishes, at least two species of "placoderms," and an acanthodian—nearly all of them in large numbers of individuals. A few species of invertebrates accompanied the vertebrates. Of these, very great numbers of *Concavicaris sinuata*, a crustacean, entered during the second and third wet seasons.

During the dry seasons the organisms became concentrated in residual ponds. The burial density of the vertebrates indicates a supersaturation of the population in these ponds leading to mortality due to predation and mutilation but not to complete destruction of the fauna by the end of each of these transient episodes.

The sharp difference between the pioneering communities of the first (marine) and the subsequent fresh to brackish transient environments tends to suggest rather strongly that *Dunbarella*, alone among the pioneers, was a strictly stenohaline animal, incapable of adjusting to marked variations in salinity. The other elements of the fauna, and the *flotant* vegetation, appear to have been euryhaline.

This interpretation poses no problems so far as the vegetation (Pearse and Gunter, 1957) and the fishes are concerned. Gunter (1938, 1942; and in Pearse and Gunter, 1957) suggested that euryhalinity may possibly have been more prevalent among ancient fishes than among those of today. The cephalopods, on the other hand, have been considered strictly stenohaline. In view of the present evidence this would appear to be doubtful so far as concerns those species in the black sheety shales.[1]

The reasons for the mass invasion of the former coastal plain during the rainy seasons by vast numbers of fishes may be simply the availability of new *Lebensraum* as stated for the initial marine inundation, but there is some evidence of additional reasons that might well be considered significant. Spectrographic analysis of the shales from Mecca Quarry shows high concentrations of a number of elements in the black levels above level D but rather low concentrations in level D. These concentrations might reflect the nutrient content of the waters in which the shales were formed. If this be granted, we may conclude that the marine waters of the epicontinental sea were relatively poor in nutrient content, those of the stream-borne fresh water rich. We may thus tentatively suggest the possibility that the pioneers entered this temporary fresh, or at best brackish, water situation in search of food. This would certainly explain the invasion of this environment by enormous numbers of individuals. Toward the end of sheety shale deposition, in most localities about four years after the onset of the transgression, the gradual subsidence of the coastal plain had reached the point where even during the dry seasons the water cover remained deep enough all over so that mass concentrations of nutrients and animals no longer occurred.

While this suggestion seems reasonable, it is necessary to point out that we found absolutely no evidence of a food source outside of the invading fauna itself. None of the faunal elements of the fresh-water fauna of Garrard Quarry, for example, were seen in any of the gastric residues. It is also pertinent to mention in this connection that "Marine animals as a whole are better able to tolerate a lowering of salinity than fresh-water animals to tolerate a rise in salinity . . . which accounts for the fact that brackish-water, bay, and estuarine faunas are marine and not fresh-water." (Gunter, 1947, p. 77.)

D. THE ECOLOGY OF THE RESIDUAL PONDS

During the dry seasons following the first pulse of the transgression, residual pond situations developed over the coastal plain. The pioneer communities that invaded the newly formed transient environments during the rainy seasons were gradually concentrated in these places and it is here that the population densities reached fantastic proportions. Any topographic depression on the coastal plain—be it a slight pan on the floor of the coal swamp, an oxbow, or a shallow, blocked bayou—appears to have become a residual pond. None of these depressions could have been more than a very few feet lower than the surrounding country, since nearly all of them are underlain by autochthonous coal or marsh deposits. At the time of peat deposition they may have been little more than wet situations within the coal forest. After the first inundation the coastal plain remained under a cover of water, probably only a few inches deep and only slightly deeper, a few feet at the most, in the residual ponds. A floating mat of vegetation, very likely algal in character, developed all over the area. In most places it may have been in contact with the bottom mud—hence the scarcity or absence of fossil content—but in the ponds it was a true *flotant*. As such it prevented disturbance of the water by wind and waves. The water was extremely quiet but not stagnant. Indirect evidence suggests that the *flotant* may have been a mat dense enough to deny light to the water beneath.

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[1] The assumption that the presence of cephalopods invalidates our interpretation of the environment and that the waters in question were of about the same salinity as those of the adjacent epicontinental sea, raises the even more vexing question as to why *Dunbarella* occurs consistently (in all transgression sequences observed) only in the basal levels where the question of salinity is not in doubt. We have found no evidence, other than the unsuitability of the environment, to explain this phenomenon. The situation demonstrates rather dramatically that environmental interpretations, based on a single line of evidence—in this case the presence of cephalopods—may be grossly misleading.

We have no evidence concerning the temperature regime of these ponds, except the one fact that none of the trapped, densely crowded animals died of any cause other than predation or injury;[1] hence the temperature regime must have been within the tolerance limits of all of the different species. The same statement applies to the pH and the oxygen–carbon dioxide balance of the water in the residual ponds. A salinity difference was mentioned above between the waters of the first year of the transgression (saline), and those of the second to fourth years (fresh to brackish). But there is no evidence to suggest that the residual ponds ever became notably hypersaline, as happens, on occasion, in similar places today (Gunter, 1952).

The bottoms of the residual ponds consisted of black carbonaceous muds, primarily decomposition products of the *flotant* vegetation beneath a column of minestra-like, comminuted plant debris. Silt was present, but in very small quantities. Significant additions to the muds were degradation products of animal origin and quantities of skeletal material. The process of decomposition was rapid and so was burial. This aspect of the problem is documented by a wealth of unusually striking evidence. The interstitial water of the sediment was no doubt severely deoxygenated as a result of aerobic decomposition, and anaerobic conditions were readily established beneath the decomposing carcasses of the vertebrates. Methane, H_2S and ammonia must have been present in the mud.

Rough calculations were made of the population density of the fishes for the Mecca and Logan Quarry sites, in terms of volume of fish per volume of water occupied by the fishes. The figures lie between 1:5 and 1:287 for the Mecca Quarry and between 1:31 and 1:1830 for the Logan Quarry. Each pair of figures represents minimal and almost certainly maximal values. The true ratio is likely to have been somewhat below the maximal figures. The high value for Mecca Quarry indicates a degree of crowding about fourteen times as great as that observable in overcrowded, experimental fish ponds. It may seem incredible that a shallow, restricted body of water over a mud of the type described and covered by a mat of vegetation, could have supported a large, excessively crowded population of vertebrates and some invertebrates over a period of several months. Yet all of the evidence clearly indicates that this was indeed the case, and furthermore that the adversity of the environment was not the direct cause of mass mortality in these places. The question thus arises as to what factors might have brought about the following necessary circumstances: an oxygen–carbon dioxide balance adequate for the maintenance of animal life in high population concentration; prevention of putrefaction of the water from large quantities of decomposing animal and vegetable material; maintenance of a food supply for the smaller elements of the pioneer community.

There is no evidence for gross water movement, but the water of the residual ponds was not stagnant. It seems likely that there was slow water seepage toward the epicontinental basin. The rate of flow cannot be determined, but it must have been sufficient to remove most of the noxious decomposition by-products that escaped during the initial phase of carcass decomposition. There is good reason to believe that the *flotant*, probably in contact with the bottom in most places other than the ponds, rendered the seeping water high in oxygen, low in carbon dioxide content. A constant flow of such water through the residual ponds, together with frequent rainfall, seems a likely explanation.

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[1] But see notation concerning *Dunbarella* (p. 135).

An explanation for the obvious absence of severe water pollution by the decomposing carcasses is better supported. A great deal of incontrovertible evidence indicates an extremely rapid rate of deposition. The carcasses were covered by a layer of sediment (for the most part fine plant degradation debris) long before their soft parts had been reduced by aerobic bacteria. The evidence, furthermore, indicates that compaction of the sediment was virtually synchronous with deposition. Hence the aerobic decomposition process was quickly terminated in favor of anaerobic decomposition, which is far slower and much less violent. Such volatile products of the anaerobic process as H_2S were held in the interstitial sediment spaces in the form of small bubbles and did not penetrate into the water above. At the site of Mecca Quarry, 1 mm. of essentially compacted mud was formed in less than one week; at Logan Quarry the comparable figure is 2 mm.

A balanced food chain did not develop in the residual ponds. In so far as the larger pioneers are concerned the food relationships are well documented. It is not clear, however, what food sustained the smaller species. The *flotant* no doubt was the main producer. It probably sheltered a host of small consumers of which there is no fossil evidence. The small fishes and the phyllocarids may have fed on these, but their numbers were so large in the residual ponds that it seems doubtful to us that a food source of this kind could have been adequate. Even less likely is the possibility that they fed entirely on the *flotant* vegetation.

Coprolites attributable to medium-sized consumers (probably mostly palaeoniscoid fishes) occasionally contain minute fragments of well-digested bone or other vertebrate skeletal material. This would indicate that these animals utilized a food source that was in abundant supply in the residual ponds, namely, the remains of mutilated prey left by the larger predators, ingested before they reached the bottom. Disgorged stomach residues of sharks show that these animals ate palaeoniscoid fishes, acanthodians, "placoderms," and other sharks as well as phyllocarids and cephalopods, and in virtually every possible combination. The food habits of these pioneers thus were unspecific, and such dietary specificity as may have characterized individual species had broken down under the adversities of entrapment in the residual ponds.

One aspect of the feeding behavior of the sharks deserves special note. Among many hundreds of specimens of vertebrates in our collection there is not a single individual that can be definitely identified as having died of causes other than predation or mutilation. To what extent this reflects inefficient feeding behavior due to the availability of large numbers of prey, or voracity beyond the satisfaction of hunger, or difficulties in the performance of the feeding manoeuvre due to shallow water and excessive crowding, cannot be determined.

E. THE ECOLOGY OF THE MARGINAL FRESH-WATER SITUATIONS

The compound physiographic zone represented by the outcrop belt of the Logan Quarry shale includes, in the area of our study, a fresh-water lake or oxbow (Garrard Quarry), and laterally situations that may be interpreted as fresh-water marshlands (Woodland and Trumpet valleys). The histories of these places pre-date the marine transgression, and their deposits were formed during a time when peat was laid down laterally. Superimposed on these fresh-water sediments is the typical transgression facies of the Logan Quarry shale. Since the fresh-water situation is adequately known only at Garrard Quarry the following account will be restricted to this site.

At the time when peat was deposited elsewhere along the coastal plain, the site of Garrard Quarry was a topographic low of undeterminable size. It may have been a lake, a pond, or an oxbow, the latter being most likely. It contained fresh water and was drained, probably through marshland, by an ill-defined bayou that may have been connected with the Logan site, half a mile to the southwest. At first this body of water was surrounded by coal forest; dead trees of various sizes were washed into it and settled crisscross at the bottom, producing a layer of "coal" consisting almost wholly of stems.

The depth of water cannot be ascertained, but was probably no more than a few feet. If there was an animal community present at this time, its remains were not preserved.

Then the surrounding region changed, the coal forest having been replaced by some kind of marsh, and the deposition of logs ceased. Instead, the bottom became covered with a black, unevenly bedded mud. An animal community dominated by the mussel *Myalina* inhabited the site during this phase. *Myalina* developed a tremendous population density. Smaller numbers of a fresh-water shrimp, small palaeoniscoid fishes (several species), a large (?)rhipidistian, perhaps a lungfish, a pleuracanthid shark, and a small acanthodian[1] characterized this fresh-water community.

Since it is not possible to determine synchronous events at the site of Garrard Quarry and the nearby Logan Quarry the following account is merely one among several possible interpretations.

The environment as described above lasted for but a relatively short time; it then became stagnant; great quantities of sulfides were retained in the mud. It seems likely that these changes were related to slight down-warping movements that took place all along the coastal plain. As was pointed out above, such crustal movements, however slight, were probably accompanied by mild tremors that had the effect of compacting loosely deposited sediments; thus the significant lowering of the coastal plain was both a direct and an indirect result of the tectonic activity. At the site of Logan Quarry this led to the initial transgression flood. At Garrard Quarry it merely interfered with drainage.

At this time the fresh-water community was gradually destroyed, probably due to poisoning by noxious decomposition products, primarily H_2S. The destruction, however, was not a single event; it took place over a period of time, during which the environment of deposition was entirely quiet and the site was probably covered by a *flotant* (Zone 6). The marine transgression reached this site near the end of the quiet water period. A few marine invertebrates, for example *Lingula* and *Dunbarella*, first appeared in the top 2 mm. of Zone 6, while a few elements of the fresh-water community lingered on. Although there is no obvious evidence in the depositional record, it seems likely that the formerly fresh water became brackish at this time.

There followed an episode when clastics were introduced (rainy season?), forming a dark gray mud in which countless individuals of *Dunbarella* were buried. These animals must have died either because of the presence of poisonous substances in the bottom mud or because of the influx of fresh water which they could not survive. Predation was definitely not a factor. Along with *Dunbarella* a few cephalopods (but none of the typical fishes of the Mecca and Logan Quarry shales) reached this site.

Gradually the Garrard site became less stagnant and hence less toxic. A layer of black mud was deposited similar in character to the black muds of the Logan Quarry sequence. It contained very few individuals of *Dunbarella* and *Pseudorthoceras* but no goniatites.

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[1] This is probably the same species as occurs in the Mecca and Logan Quarry transitional environments, and hence the only faunal element present in both assemblages.

V. BROADER IMPLICATIONS

The following remarks are not to be taken as primary results of the present study since they are not based on complete evidence. Rather they are hints of broader relationships based on some of our conclusions.

The history of any small area is part of the history of the broader region to which it belongs. Both regional and local influences determine the environment and its history. Thus the history of the Minshall-to-Velpen interval in Parke County is an expression of conditions pertaining to the Illinois Basin province as a whole, though the specific character of events at any moment in time and at any point on the map are also determined by local circumstances. Hence it should be possible to arrive at suggestions concerning the broader aspects of the basin history, provided that local factors can be distinguished from those that operated regionally.

A. It is a curious fact that at least four transgressive sheety black shale horizons in this particular area represent, along their outcrop belts, essentially the same physiographic zones on the margin of a coastal plain adjacent to the epicontinental sea. This would suggest that the fringe of the sea recurrently occupied a definite line running approximately north from Montezuma to Newport and northwestward toward Danville, Illinois. From this line it repeatedly transgressed eastward (fig. 51).

During these periods of pause, maturely differentiated biotopes developed on the coastal plain and off the shore. Examples of these, described above, are the fresh-water situation at Garrard Quarry and the productid-coral banks near West Montezuma.

During an appreciable period of stillstand preceding the deposition of the Mecca Quarry shale, a delta developed and persisted between Montezuma and Newport (fig. 46).

The greater thickness of the sedimentary column within the Illinois Basin than along its periphery ("transition zone," fig. 6) shows that the basin sank the more rapidly; hence a hinge line on its margin is not unexpected.

Concentrations of the Mecca fauna appear to be absent throughout the basin province except on the margin (see C, below). This lends additional weight to the suggestion that maturely developed biotopes were established during a stillstand before the transgression in each of the four episodes. During the flooding of the basin proper, the rate of transgression may have been too rapid to permit a large population to develop in the relatively transient offshore zone, and too rapid to have allowed ponding during dry seasons.

Such interpretations regarding areas not directly observed, and the many implications affecting regional stratigraphic relations, lie far beyond the proper limits of this study.

B. The extraordinary faunal concentrations in residual ponds in the area described resulted from local, rather than regional, conditions: essentially, relief of the peat floor and slope of the coastal plain. It is to be expected that similar concentrations will be found here and there wherever similar local conditions existed within the same regional framework. We have seen, but have not intensively studied, one locality of suspected concentration, in Kankakee County, Illinois (now inaccessible); another, from which F. R. Jelliff collected in the late nineteenth century, may still exist near Galesburg in Knox County, Illinois. Both of these incompletely known localities are marginal to the deep basin. If such localities contain large concentrations of fossil vertebrates, they should be studied to determine the record of climate and of rate of deposition.

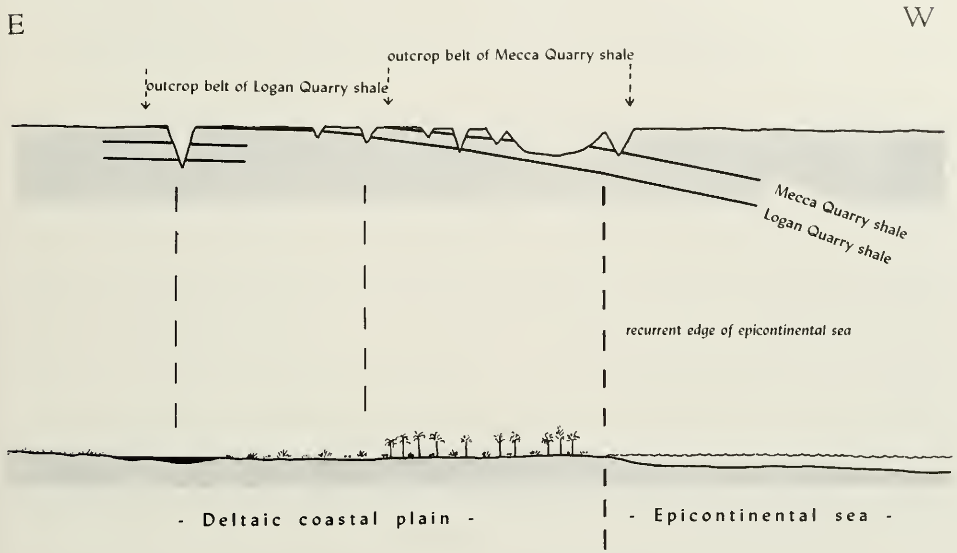
E
W
outcrop belt of Mecca Quarry shale
outcrop belt of Logan Quarry shale
Mecca Quarry shale
Logan Quarry shale
recurrent edge of epicontinental sea
- Deltaic coastal plain -
- Epicontinental sea -

FIG. 51. Outcrop belts of Logan and Mecca Quarry shales and physiographic zones represented by them, immediately before respective marine transgressions. The edge of the epicontinental sea stood recurrently at a hinge line, with greater crustal sinking to the west than to the east.

C. In petrographic character, the Mecca and Logan Quarry shales vary from true carbonaceous shale (gray levels) to coal (e.g., level G, Logan Quarry). The humulite of Garrard Quarry is petrographically coal with an extremely high sulfide content. It is probable that a systematic examination of these and similar rock types in Parke County would reveal a continuous spectrum of composition from drab shale to coal.

Since the petrology of the black shales is very much less complex than that of high grade coal, study of these shales as "diluted samples" of coal may lead to significant insights concerning the composition, origin and rate of formation of coal.

VI. OUTLINE OF THE SUPPORTING EVIDENCE OF THE MAJOR CONCLUSIONS

A coherent picture of the results obtained in this study is difficult to present in summary form; for such a presentation see SYNTHESIS (p. 213).

A paleoecological study of this magnitude presents a fabric of inter-related arguments. Thus there is an ever-present danger of circular reasoning. Many of our conclusions are supported by multiple lines of argument, including derivations from other conclusions. Any valid conclusion, however, must not only be consistent with the entire fabric, but must be based on independent, objective evidence (for a discussion of "direct" evidence in paleoecology see p. 3).

Below we list our major conclusions, along with references to the specific supporting evidence in the body of the paper.

1. The twelve-inch profile of Mecca Quarry shale was deposited in about four years.
    - (a). Aerobic decomposition speed of fish carcasses is assumed to have been the same in the Pennsylvanian as in similar, modern environments (pp. 162, 167).
    - (b). The thickness of mud accumulation over the carcasses during the aerobic phase of decomposition was uniform and measurable (pp. 170, 172).
2. Compaction of the Mecca and Logan Quarry shales was synchronous with deposition.
    - (a). Cavities in bone were filled with air; spongy bone was not crushed (p. 178).
    - (b). Decomposed cartilage void within calcified cartilage elements was not filled with sediment (pl. 51, fig. 40, and pp. 178–179).
    - (c). Gases produced during anaerobic decomposition were not vented to surface (p. 179).
    - (d). Fossils were occasionally preserved at high angle to bedding (p. 181).
3. The Mecca and Logan Quarry shales record the initial phases of marine transgressions.
    - (a). The sheety shales contain a marine fauna (p. 184).
    - (b). The sheety shales overlie a non-marine substrate: coal beneath Mecca Quarry shale (see p. 198); humulite beneath Logan Quarry shale (p. 187).
    - (c). The sheety shales grade upward into marine limestone through drab marine shale.
4. The water was shoal, but varied in depth.
    - (a). It is unlikely to have been deep immediately following the transgression; there is no evidence of local tectonic effects (pp. 21, 190). It was very shallow during black mud deposition.
    - (b). In level J (Logan Quarry, it very nearly dried up (pp. 24, 136).
    - (c). High fossil concentration at certain localities indicates residual ponding, hence very shallow water (pp. 153, 188). It was deeper during gray mud deposition (p. 119).
    - (d). Slight orientation of particles in level C (Mecca Quarry) indicates slight water movement, hence higher water (p. 160).

    (e). Large wagon-wheel cephalopods in level F (Logan Quarry) required at least three feet of water (p. 31).
    (f). A variable amount of clay was superimposed on a constant rain of plant debris; hence influx of water, hence deeper water (pp. 31, 110).

5. Concentration of the burial community was effected in residual ponds on the coastal plain during the dry seasons.
    (a). Concentrations of fossils occur in successive black levels at certain localities, e.g., Mecca Quarry (fig. 32), Logan Quarry (p. 155).
    (b). Fossils are absent in black or gray levels at other localities, e.g., Barren Creek (p. 154).
    (c). Burial population was excessively dense at localities where fossil concentrations occur (p. 190 ff).
    (d). Near-drying conditions existed during deposition of level J (black band), Logan Quarry (p. 136).
    (e). Local highs acted as dams, permitting ponding in low water (p. 62).

6. The thanatocoenosis is autochthonous.
    (a). There is no evidence of transport of individuals except as gastro-intestinal content (p. 132).
    (b) There is evidence of mutilation, mouthing, active feeding and defecation (p. 134 ff).
    (c). The fauna continuously inhabited the Mecca and Logan environments; it was never completely destroyed (fig. 32).

7. The water above the bottom was inhabitable.
    (a). Evidence the same as under 6.

8. The bottom lay beneath a graded mud column (fig. 27) and provided a firm settling surface.
    (a). Dissociated fossil skeletons are always draped over a single horizontal plane, regardless of the specific gravity of the parts: heavier parts did not settle deeper than light parts (pp. 128, 139).
    (b). Similar organic black mud columns exist in present-day bayous (p. 177); a settling surface, however, requires demonstration.

9. The bottom was extremely quiet.
    (a). The shale is extraordinarily even-bedded (pp. 16, 28, 120).
    (b). Dissociated fossil skeletons are spread on horizontal planes, irrespective of the specific gravity of the parts: light parts were not differentially swept away (p. 128).
    (c). There is no orientation of particles (p. 156), except for a slight indication in level C (Mecca Quarry).
    (d). Areal distribution of fossil content at Mecca Quarry appears to be random (p. 144).

10. The bottom was toxic.
    (a). There is no evidence of disturbance by scavengers (p. 195).
    (b). There was neither infauna nor benthos (pp. 28, 184).
    (c). Aerobic decay was quickly terminated and was succeeded by anaerobic conditions (pp. 164, 179).

(d). Sulfides and sulfates were formed penecontemporaneously with deposition on carcasses and gastric residues (pp. 165, 179).

(e) At Garrard Quarry *Dunbarella* are preserved intact with both valves together, suggesting that they died quickly, perhaps were poisoned upon touching the bottom (p. 135).

(f). Plant debris of black levels was not wholly oxidized (pp. 110, 118).

(g). Some modern bayou black mud situations have toxic bottoms (p. 177).

11. The bottom was extremely stagnant at Garrard Quarry prior to and during the initial phases of the transgression.

(a). Excessive amounts of finely dispersed sulfides rendered humulite and shale olive-green in color (pp. 97, 113).

12. Water regime was initially fresh water (prior to the transgression) at Garrard Quarry.

(a). The fauna was radically different from the Mecca fauna (except possibly for an acanthodian); it includes a pleuracanthid shark (p. 187).

13. The water regimen of the Mecca and Logan Quarry shales was initially salt, succeeded by brackish to fresh, and ultimately salt again.

(a). The pectinid *Dunbarella* is present in the basal black shale levels and absent in succeeding sheety shale levels (pp. 124, 184).

(b). The unique fauna of the sheety shales was succeeded by normal marine fauna in the shales above (p. 28).

(c). The high trace element concentration is high in levels C to A and relatively low in basal marine level D (Mecca Quarry) (p. 97 ff).

14. The pre-transgression surface was topographically uneven; after the initial inundation a complex archipelago–bayou topography resulted (pp. 24 ff.).

(a). There is evidence of drainageways through the pear swamp (pp. 40, 94, 209).

(b). Channel clod occurs in a number of localities (pp. 39, 48, 58, fig. 9).

(c). There was local higher ground at West Montezuma (p. 62).

(d). The diversity of stratigraphic sections at Arketex clay pit (p. 63) indicates a diversified surface of deposition.

(e). At Logan Quarry there was a channel prior to the transgression (pp. 185, 212).

(f). There was post-coal depositional diversity at Dosdange Creek (p. 76).

(g). A stagnant fresh-water situation existed at Garrard Quarry (p. 125).

(h). Fossils were concentrated only at certain localities, indicating locally deeper water, hence shallow depressions in the substrate (p. 154).

(i). The Logan Quarry coal was very probably allochthonous (p. 29), except at Collings Creek (p. 52); hence the higher peat surface at Collings Creek.

15. The upper bench and the parting of Coal IIIA are more persistent than the lower bench (fig. 45, *b*).

(a). The petrographic composition of the lower bench differs from that of the upper bench and the single bench (p. 201).

16. There was a well-developed delta in pre-Coal IIIA time south of Newport, Indiana.
    (a). Clastic sediments with upwardly decreasing grain size occur in the area between Montezuma and Newport (p. 201).
    (b). Coal III and the lower bench of Coal IIIA pinch out on either side of these sediments (fig. 45,*b*).

17. The epicontinental sea lay west or southwest of the present outcrop belts of the Mecca and Logan Quarry shales (p. 62).
    (a). In the Mecca Quarry shale the channel clods and the transgression shell breccia are best developed in the southwesternmost localities (p. 94).
    (b). In the Logan Quarry shale the marine molluscan (*Dunbarella*) facies is best developed in the southwestern localities, the fresh-water humulites in the northeastern localities (see description of stratigraphic sections, p. 33 ff).

18. The outcrop belt of the Logan Quarry shale represents a physiographic zone (during deposition) slightly landward from that of the Mecca Quarry shale.
    (a). The Mecca Quarry shale contains a basal transgression shell breccia and channel clods (p. 94); these facies are absent in the Logan Quarry shale.
    (b). The Logan Quarry shale rests on a fresh-water humulite (p. 94); this facies is not represented beneath the Mecca Quarry shale.
    (c). Both shales contain extreme, local fossil concentrations.

19. The individuals of the burial community of the Mecca and Logan Quarry shales died of the effects of predation.
    (a). All individuals (so far as we know) show signs of bite injury (p. 136 ff).
    (b). Many individuals are preserved as gastric residues and coprolites (p. 138 ff).

20. The Mecca fauna invaded the burial site from its natural habitat farther seaward.
    (a). Fragmentary elements of this fauna are found occasionally in limestones and drab marine shales.
    (b). The population was replenished from time to time over the burial ground (fig. 32); it was also available for pioneering during all four transgressions in the Minshall to Velpen interval (pp. 155, 198).
    (c). A few coprolites contain crinoids and pebbles not otherwise found in the shales (p. 142).
    (d). The trophic relationships among the faunal elements were abnormal (p. 193 ff).
    (e). There was an undue proportion of predators in the Mecca and Logan burial communities, indicating that the balanced community lived elsewhere (p. 195).

The following statements are not based directly on primary evidence but they do not conflict with any of the evidence presently at hand.

1. All transgressive sheety shales (in the Minshall to Velpen interval) with their alternating sequence of black and gray levels were formed beneath a very shallow water cover.
    (a). They always occur at the very base of each transgressive sequence; hence were formed following the initial thrust of each transgression (p. 33 ff).
    (b). In the higher part of the sheety sequence the marked gray–black alternation dies out.

   (c). The deposition of the sheety shale sequence at Mecca Quarry required only about four years; to judge by the number of alternating levels in the other sheety shale horizons, the rate of deposition was probably the same in all of them.

   (d). Burial concentrations are less pronounced near the top of the sheety shale sequence and non-existing in the shales above them; hence there was no residual ponding and therefore the water was deeper toward the end of sheety shale deposition.

   (e). It seems unreasonable to suppose that a rainy–dry season climate existed only during times of sheety shale deposition (p. 215). It seems safe to assume that the same type of climate persisted all during the Minshall to Velpen interval. The periodic sequence of alternate lithologies (gray–black levels) in step with a seasonal wet–dry cycle (see Rate of Deposition, p. 172) is found only in the sheety shale horiznos, suggesting that the sheety shales are very sensitive indicators of water depth. Against a background of deeper water (A plus and marine drab shales), the increment of water and silt during a rainy season makes no perceptible difference.

2. The water surface over the Mecca and Logan depositional environments was inhabited by a floating mat of vegetation (*flotant*).

   (a). There was no disturbance by wind and wave action on the bottom of shallow water bodies.

   (b). There was a constant, local supply of plant debris (p. 121).

   (c). Lack of fossil insects and scarcity of spores in the sheety shales suggest that they were prevented from reaching the burial site (p. 121).

   (d). The black band in level J of Logan Quarry, very probably representing the floating mat of vegetation, was responsible for the unusual preservation of the large shark (PF 2201, pls. 24, B, and 25; p. 136).

   (e). The lack of fossils at Barren Creek, where the black shale levels are very highly carbonaceous (much as the black band in level J at Logan Quarry), is best interpreted as a situation in which the *flotant* was in contact with the bottom, hence preventing the animals from reaching the site.

   (f). The obviously precarious ecological conditions in the excessively crowded residual ponds virtually demand postulation of a *flotant* as a mechanism for maintaining a tolerable oxygen-carbon dioxide balance (pp. 121, 193), for shielding the ponds from direct insolation which probably would have overheated them and for providing a source of food for small consumers (p. 194).

3. The climate was "subtropical" with dry and rainy seasons.

   (a). The sheety shales indicate a depositional environment that received a continuous supply of degraded plant debris. Superposed on this is a fluctuating supply of fine clastics (fig. 25); these must have been transported by water, hence there was a fluctuating supply of water (p. 119). Driftwood sticks are larger in gray (high-water) levels than in black (low-water) levels (fig. 31, *i* and *j*). Measurement of the rate of deposition indicates that a low- and high-water cycle embraced about one year (p. 39).

4. The Mecca and Logan Quarry shales are intermediate between shale and coal in composition and gross aspect.

(a). They grade from gray shales with large amounts of clay to black levels with very little clay and on to humulite with virtually no clay (p. 105 ff).

(b). All of them contain a large amount of degraded plant debris, petrographically similar to certain coal ingredients (p. 105 ff).

(c). All of them have the gross aspects of shale rather than coal: cleavability on bedding planes; horizontal flexibility; lack of vertical blocky cleavage. They are excellent media for the preservation of fossils, especially vertebrates, in contrast to the high grade coals. There is a suggestion that some other deposits in the Parke County area may be even more perfectly intermediate between shale and coal.

5. *Dunbarella* was probably the only common stenohaline animal of the Mecca fauna; the cephalopods, the phyllocarid and the vertebrates appear to have been euryhaline.

(a). Both pectinids and cephalopods are usually found in marine deposits; where they occur in sediments of different origin, they are considered as having been washed in. In the Mecca and Logan Quarry shales there can be no doubt but that both were present alive over the burial ground. Yet *Dunbarella* is strictly confined to the basal (marine) levels of the sheety shale sequences. The cephalopods persist throughout the subsequent (brackish to fresh water) levels.

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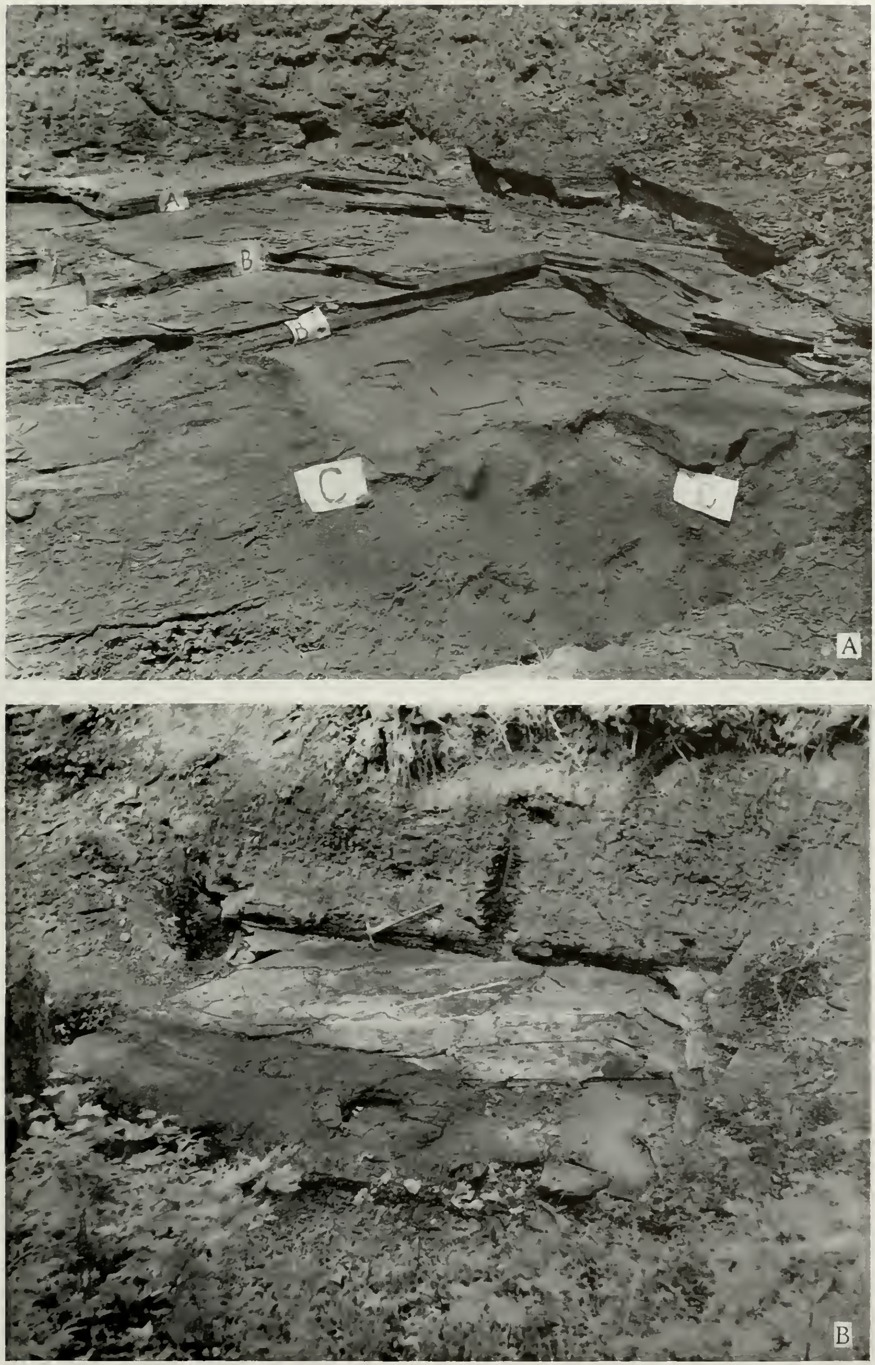
PLATES

EXPLANATION OF PLATE 1

Mecca Quarry, 1954

(A) Floor of the quarry, showing stratigraphic levels. The coal in the trench below "D" is covered by debris.

(B) Quarry floor on level B3, showing the two major joint directions present in this level.


A
B
B
C
A
B

EXPLANATION OF PLATE 2

MECCA QUARRY, 1954.

(A) Level C has been removed in the foreground to expose the large "doughnut" concretion (see also fig. 34).

(B) A section of Mecca Quarry reconstructed in a laboratory of Chicago Natural History Museum.

A

B

EXPLANATION OF PLATE 3

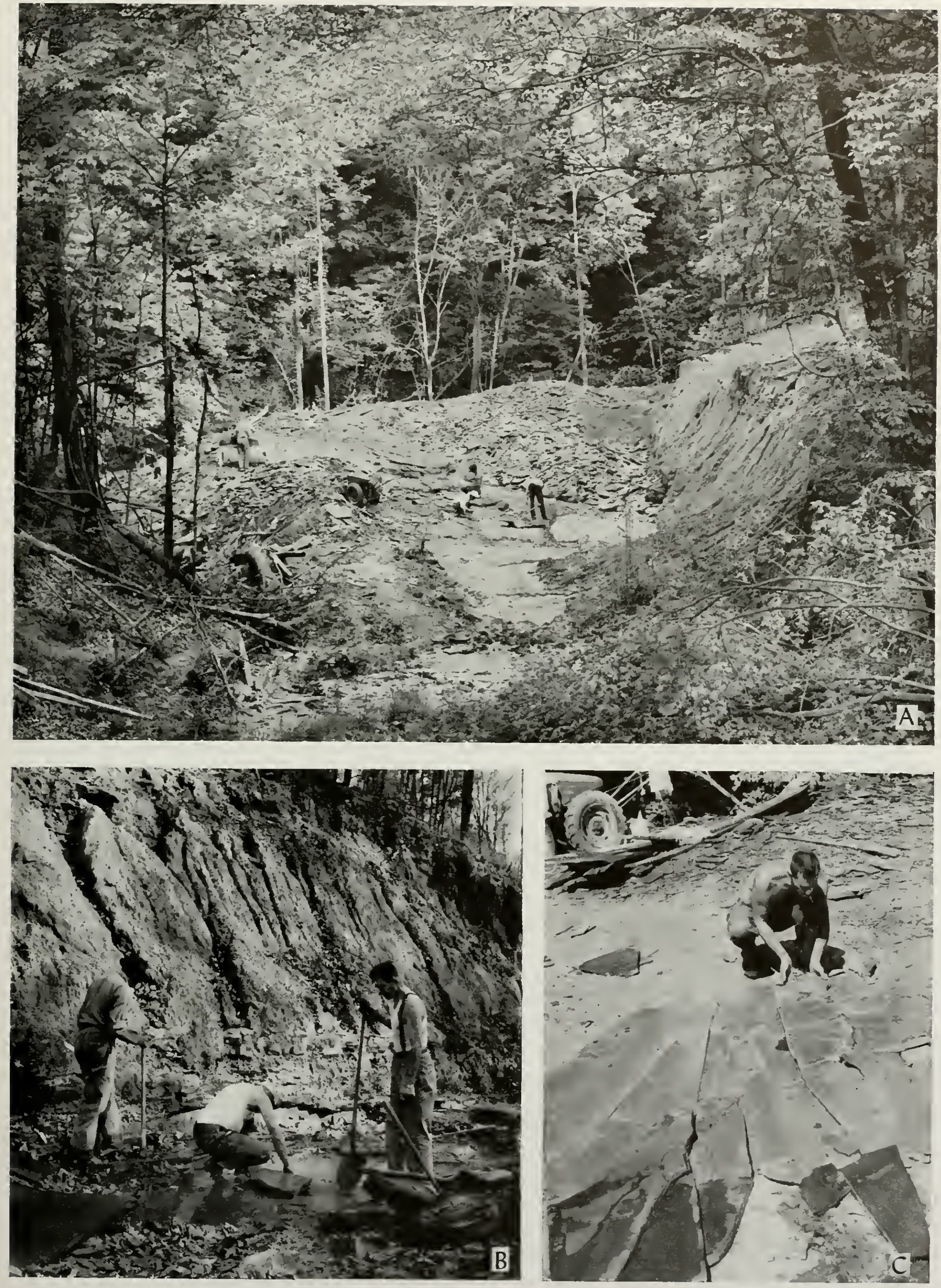
Logan Quarry, 1958.

(A) View looking north into the quarry; mud from the headwall, largely Pleistocene, had washed onto the quarry floor and was later removed. The pile of broken shale behind the workers represents shale examined and discarded (photograph by D. D. Davis).

(B) Close-up view of headwall; Pleistocene above Logan Quarry limestone at chest height. Several concretions (from level H) in right foreground. Joint blocks of level G are being removed.

(C) Joint blocks of level J being assembled beside the quarry to retain contacts of fossils that may transgress joint lines.

Plate 3

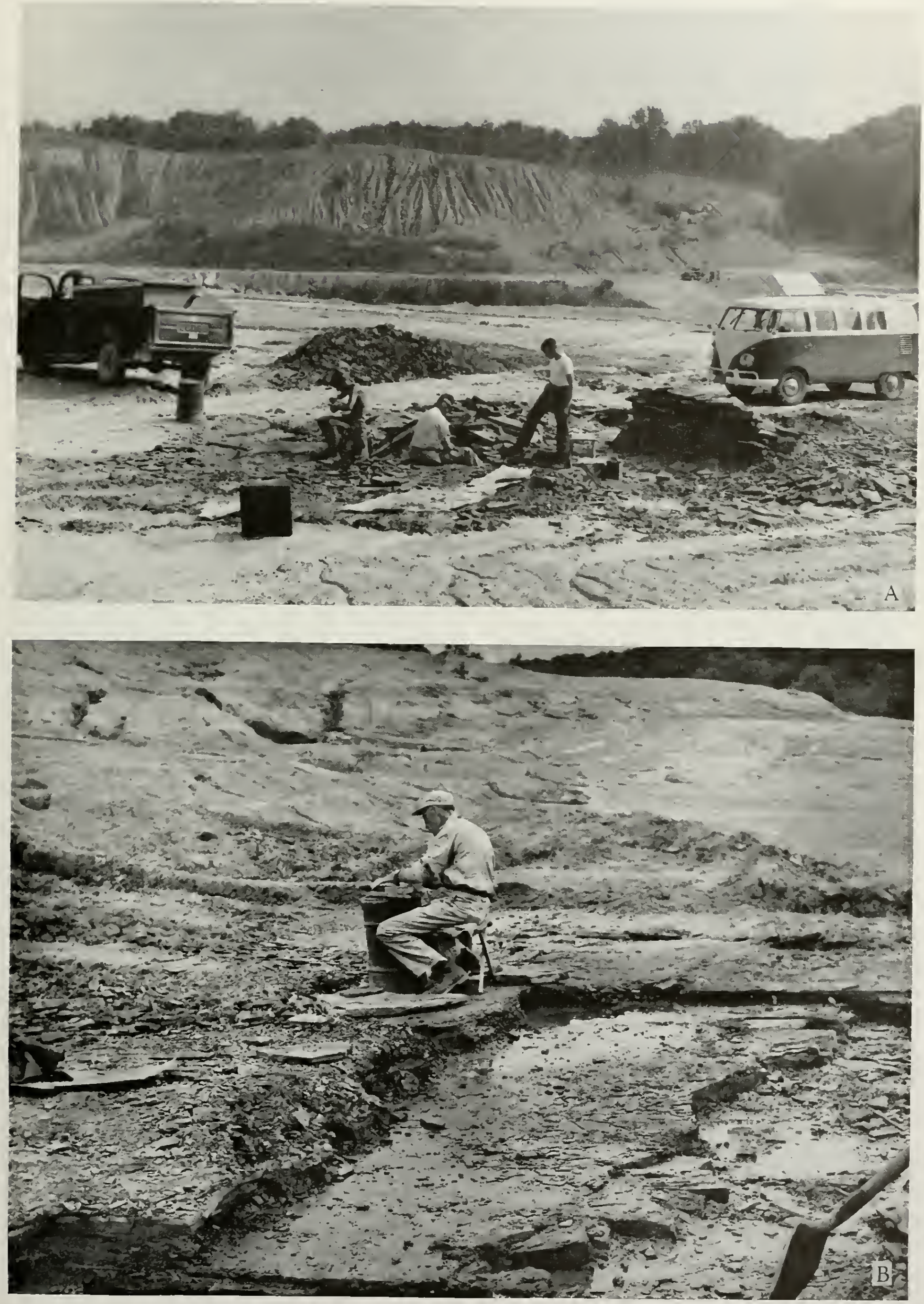


EXPLANATION OF PLATE 4

Garrard Quarry, 1960.

(A) View looking east into Cayuga Brick and Tile Corporation clay pit (photograph by D. D. Davis).

(B) Quarry floor, looking north toward Coke Oven Hollow. Humulite (Zones 4 to 6) horizontally exposed beneath worker.


A
B

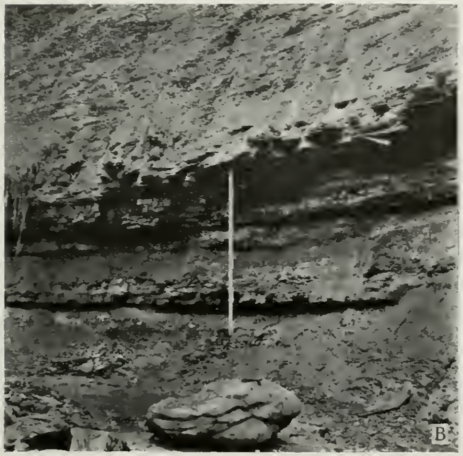
EXPLANATION OF PLATE 5

Exposures of Mecca Quarry Shale at Montgomery Creek.

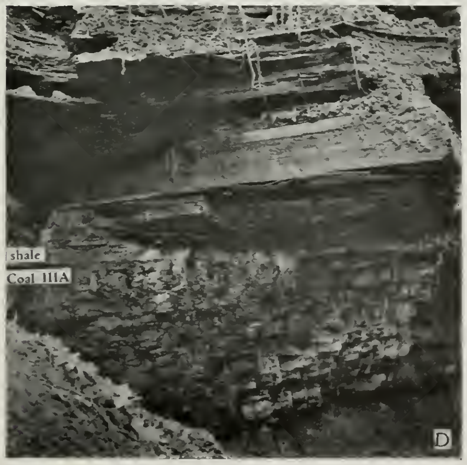
(A) Waterfall exposure.

(B–E) Details of the cliff exposure: (B) Coal III at two feet on rod, Coal IIIA at 6¾ feet on rod. Edge of channel clod approximately at rod, extending to the right. (C) Edge of channel clod above boy's head extending to the right between Coal IIIA and sheety shale. (D) Close-up of the Coal IIIA–sheety shale contact. (E) Drab shale profile above Mecca Quarry shale.

A


B

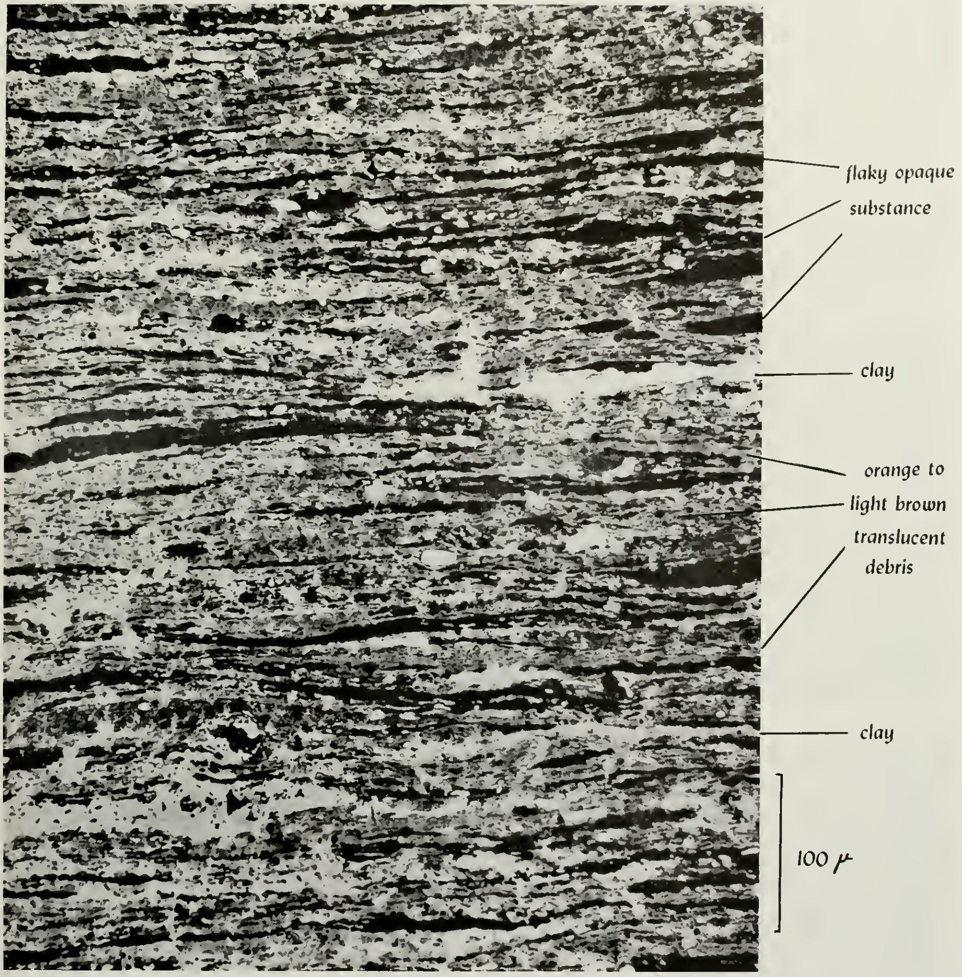
C

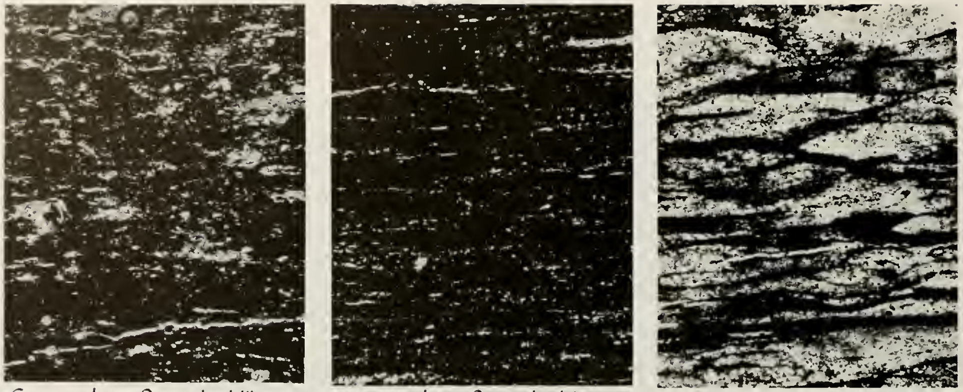

shale
Coal IIIA
D

E

EXPLANATION OF PLATE 6

Thin section, vertical to bedding, in level G (Logan Quarry).

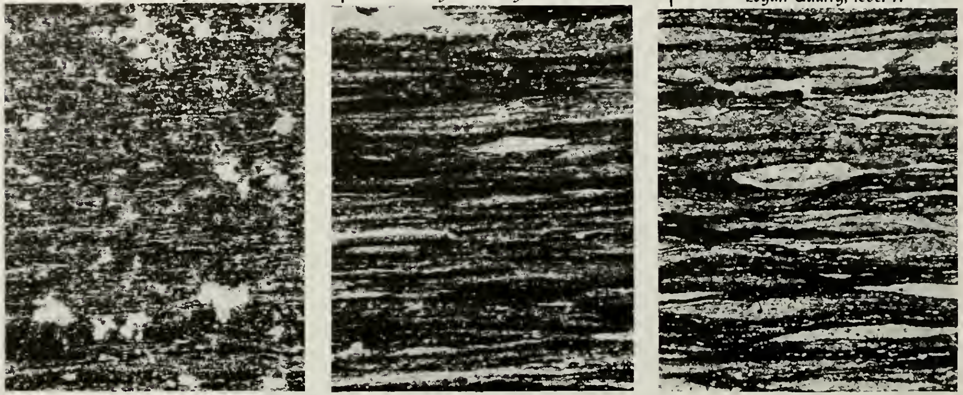

flaky opaque
substance
clay
orange to
light brown
translucent
debris
clay
100 μ



C Logan Quarry, level Kb

F Logan Quarry, level J

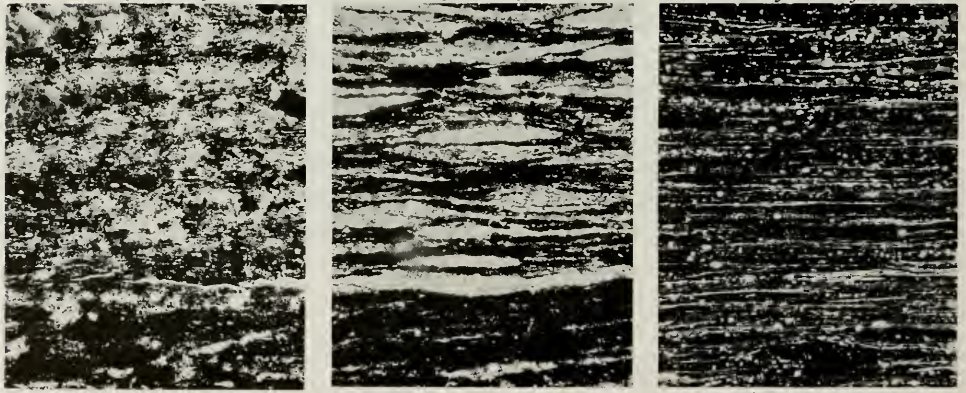
I Logan Quarry, level H



B Logan Quarry, level L

E Logan Quarry, level J

H Logan Quarry, level J

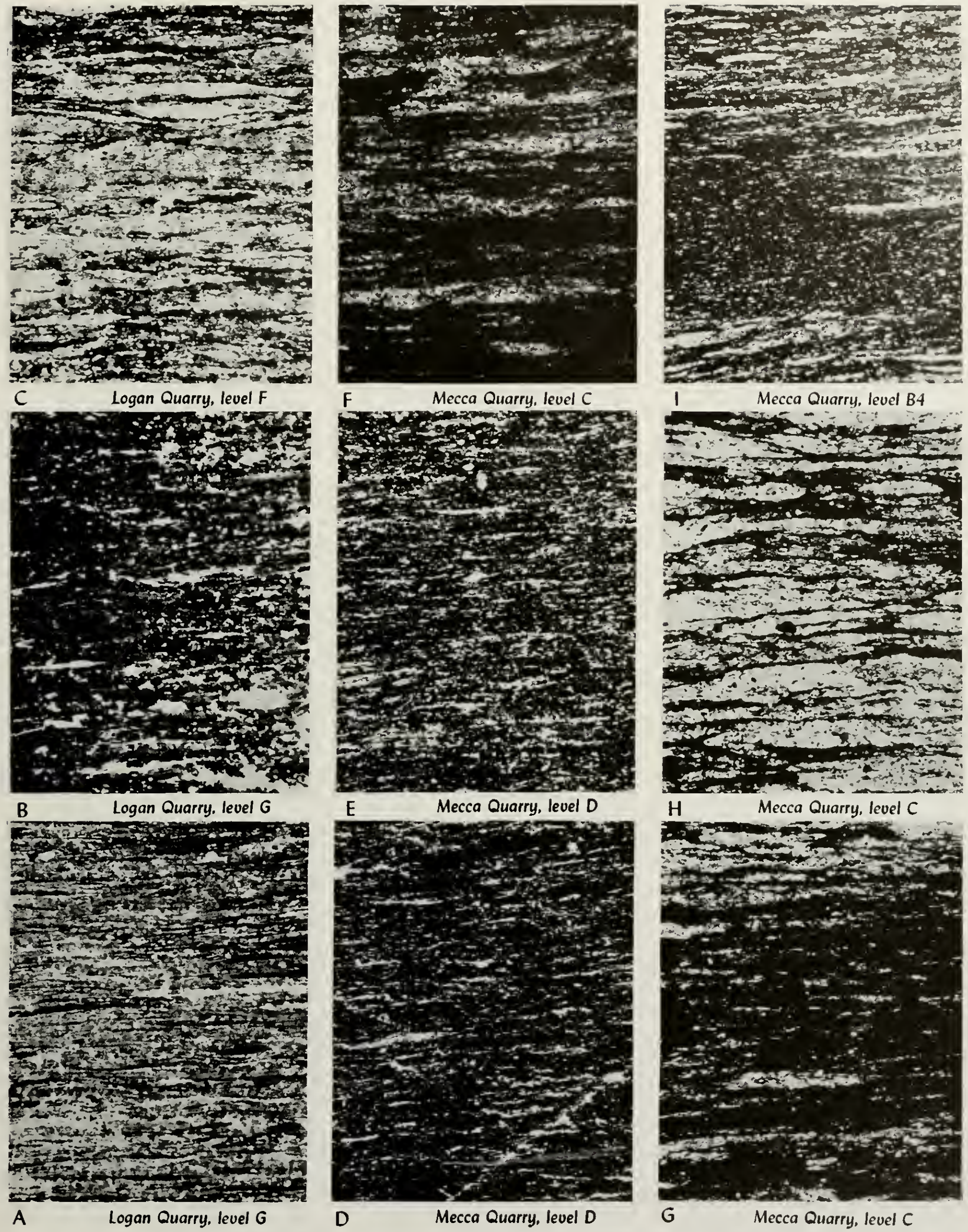


A Logan Quarry, level M

D Logan Quarry, level K

G Logan Quarry, level J

Thin sections of Logan Quarry shale at Logan Quarry, levels Kb to H. All sections vertical to bedding; (×82).



C Logan Quarry, level F

F Mecca Quarry, level C

I Mecca Quarry, level B4

B Logan Quarry, level G

E Mecca Quarry, level D

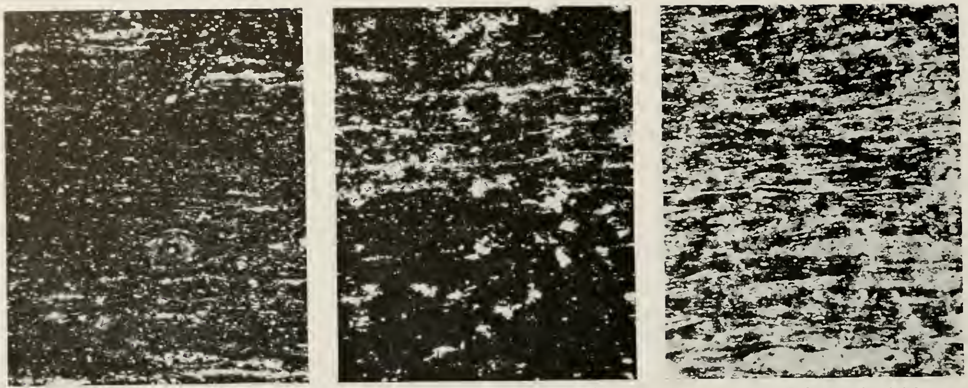
H Mecca Quarry, level C

A Logan Quarry, level G

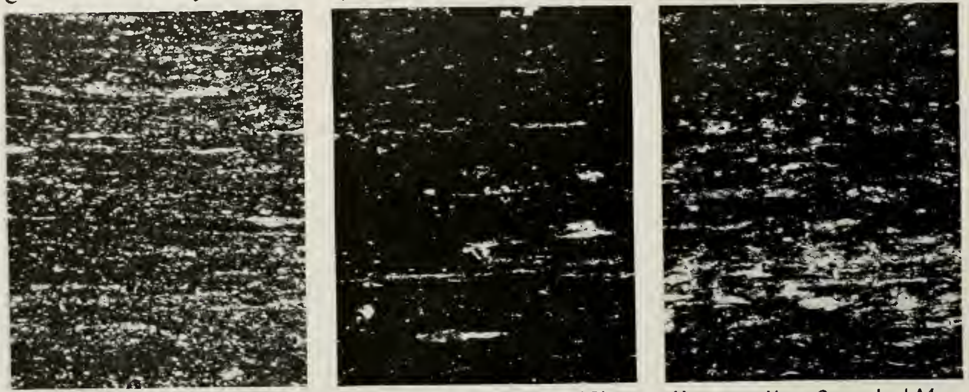
D Mecca Quarry, level D

G Mecca Quarry, level C

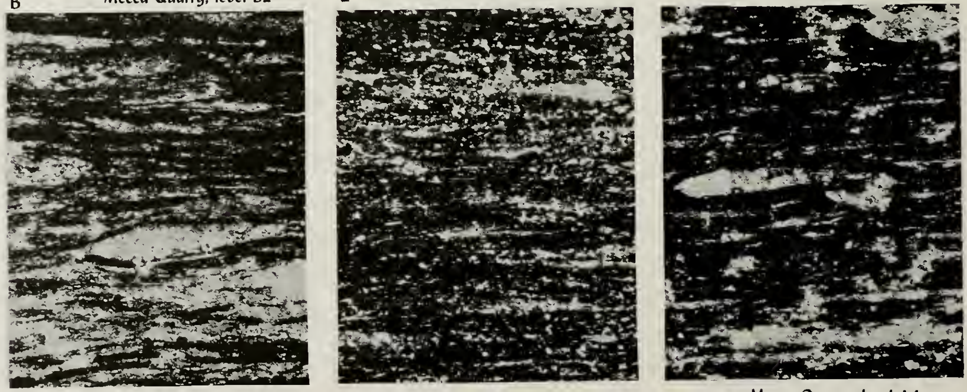
(A–C) Thin sections of Logan Quarry shale at Logan Quarry, levels G to F.
(D–I) Thin sections of Mecca Quarry shale at Mecca Quarry, levels D to B4.
All sections vertical to bedding (X 82).



C Mecca Quarry, level B2 F Mecca Quarry, level B1 I Mecca Quarry, level A4

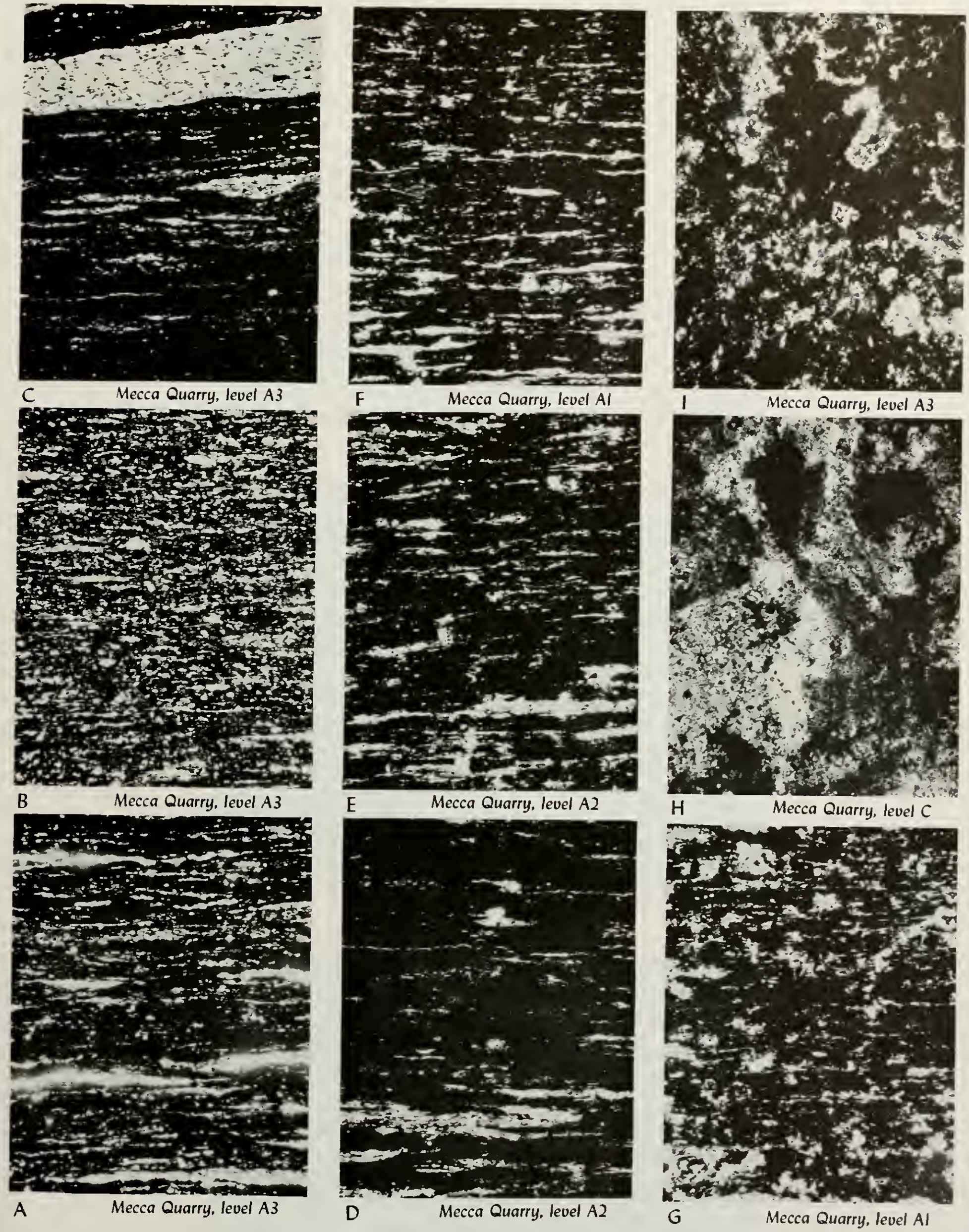


B Mecca Quarry, level B2 E Mecca Quarry, level B1 H Mecca Quarry, level A4



A Mecca Quarry, level B3 D Mecca Quarry, level B2 G Mecca Quarry, level A4

Thin sections of Mecca Quarry shale at Mecca Quarry; levels B3 to A4.
All sections vertical to bedding (× 82).



C Mecca Quarry, level A3

F Mecca Quarry, level Al

I Mecca Quarry, level A3

B Mecca Quarry, level A3

E Mecca Quarry, level A2

H Mecca Quarry, level C

A Mecca Quarry, level A3

D Mecca Quarry, level A2

G Mecca Quarry, level Al

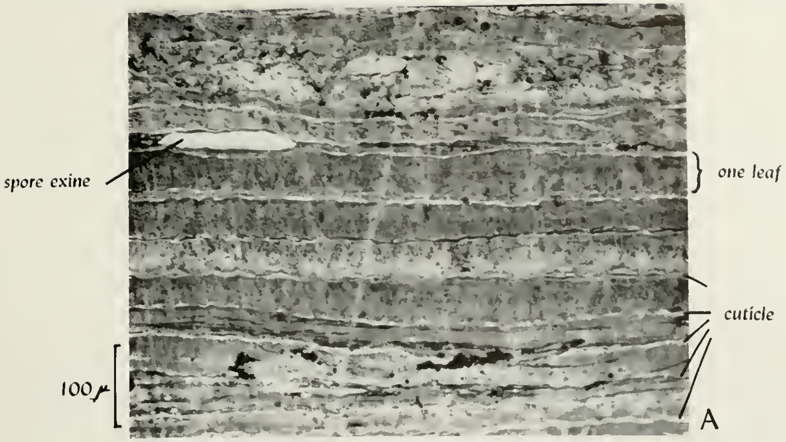
Thin sections of Mecca shale at Mecca Quarry.

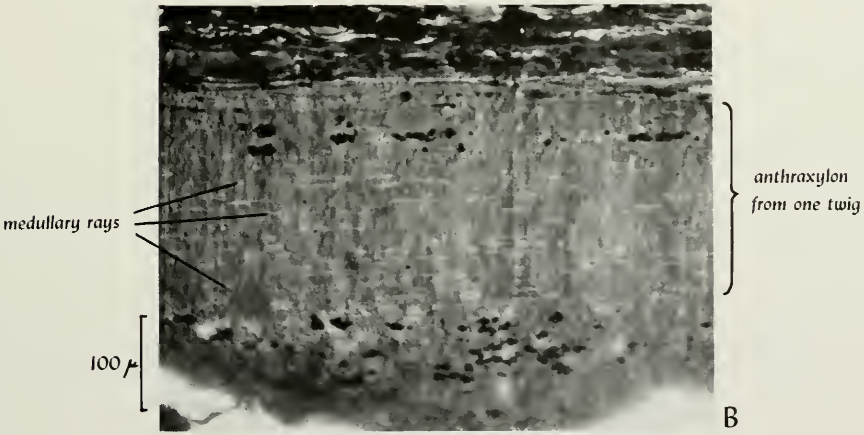
(A–G) Levels A3 to A1, vertical to bedding. (H, I) Levels C and A3 parallel to bedding. (All sections × 82.)

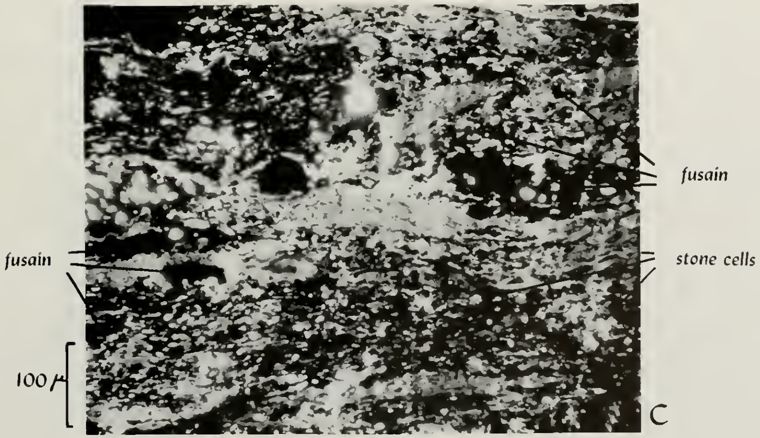
EXPLANATION OF PLATE 11

Thin sections of coal showing:

(A) Cuticularized leaves. (B) Gymnospermous anthraxylon. (C) Dull attritus.


spore exine
one leaf
cuticle
100 μ
A

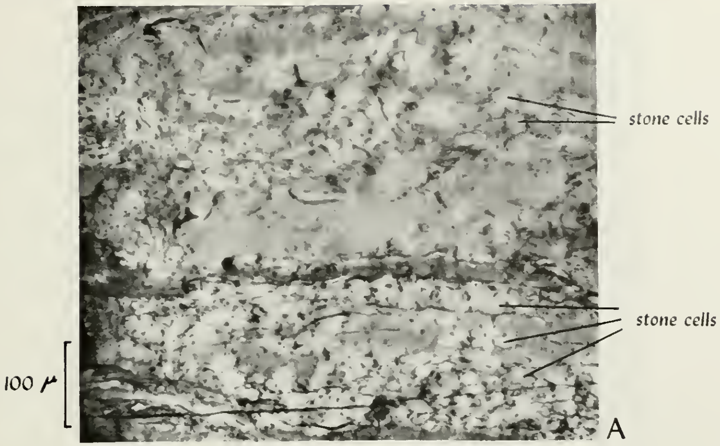

anthraxylon
from one twig
medullary rays
100 μ
B

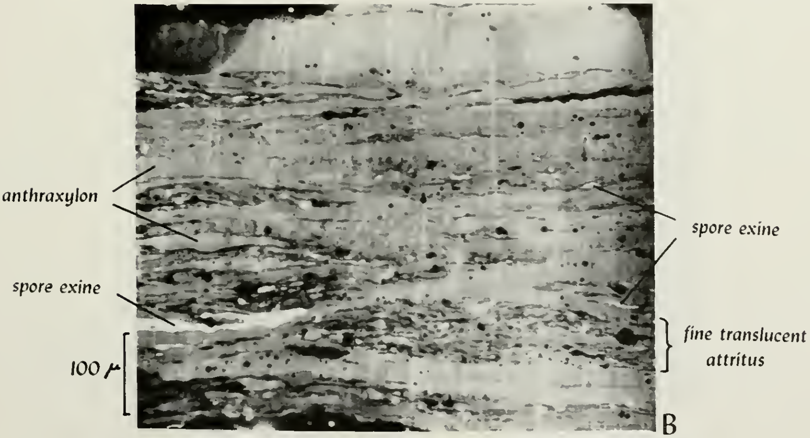

fusain
fusain
stone cells
100 μ
C

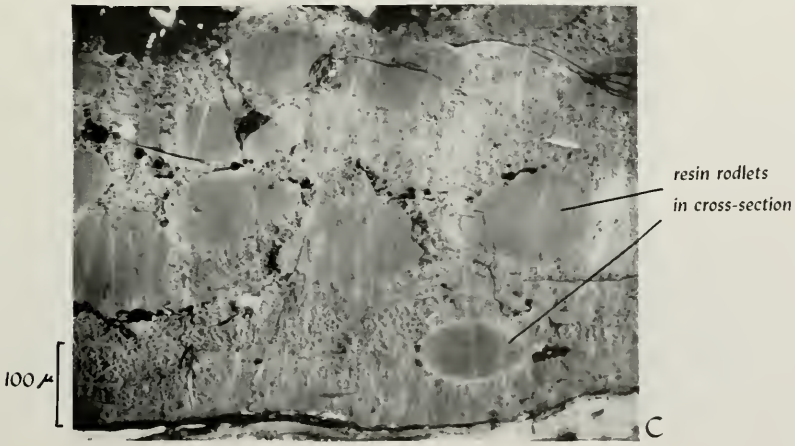
EXPLANATION OF PLATE 12

Thin sections of coal showing:

(A) Anthraxylon, almost exclusively stone cell remains. (B) "Wet" attritus.
(C) Resinous anthraxylon.


stone cells
stone cells
100 µ
A


anthraxylon
spore exine
spore exine
fine translucent attritus
100 µ
B

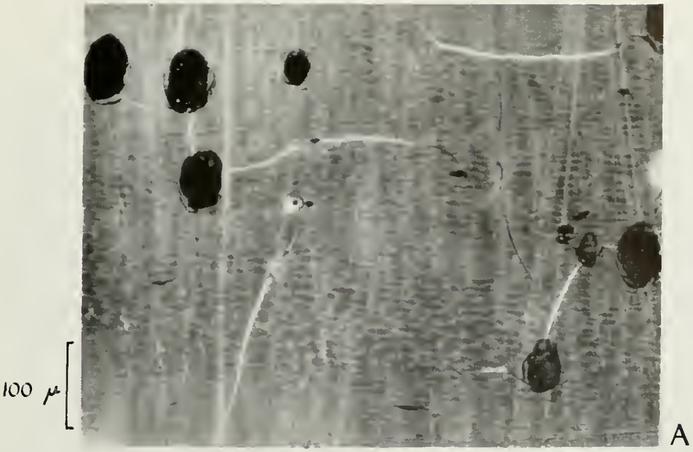

resin rodlets in cross-section
100 µ
C

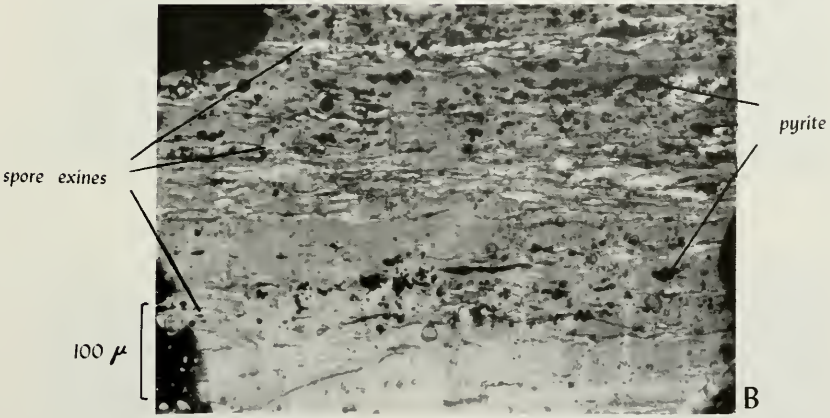
EXPLANATION OF PLATE 13

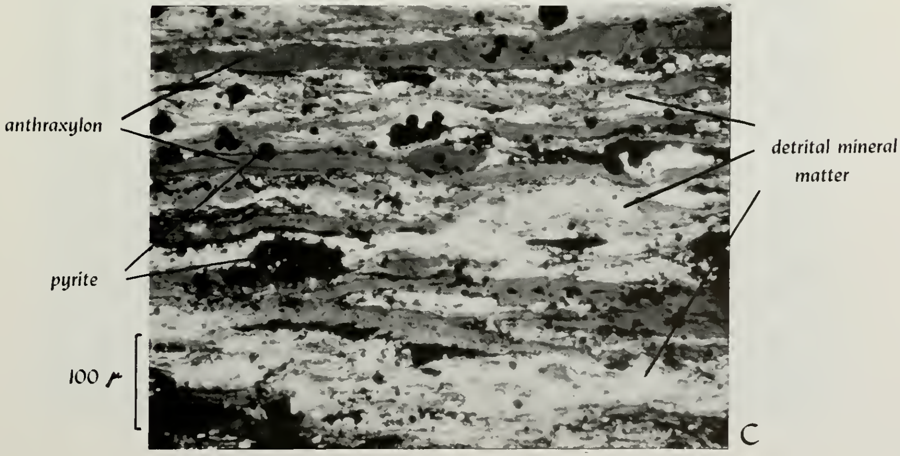
Thin sections of coal showing:

(A) Lycopod anthraxylon. (B) Pyrite in "wet" attritus.

(C) Detrital mineral matter in Logan Quarry coal at Logan Quarry.


100 μ
A


spore exines
pyrite
100 μ
B


anthraxylon
detrital mineral matter
pyrite
100 μ
C

EXPLANATION OF PLATE 14

(A) Sarpi Wildlife Refuge, Louisiana. *Flotant* over bayou near well 4 (locality 2, fig. 26); "meadow" beyond boat is vegetation floating on a body of water.

(B) Bayou Labranche east of Sarpi Wildlife Refuge, looking north (see fig. 26).

A

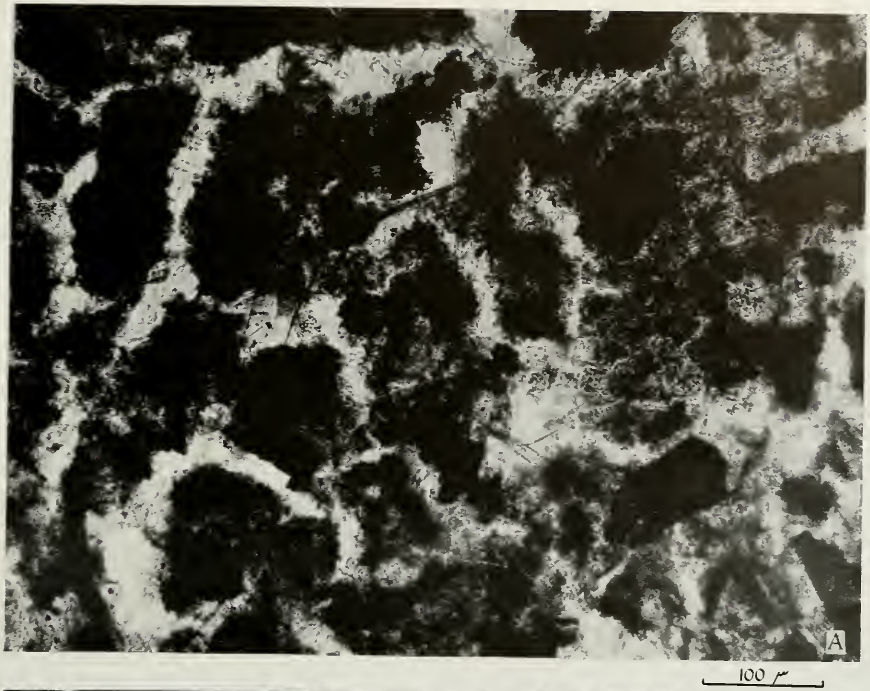
B

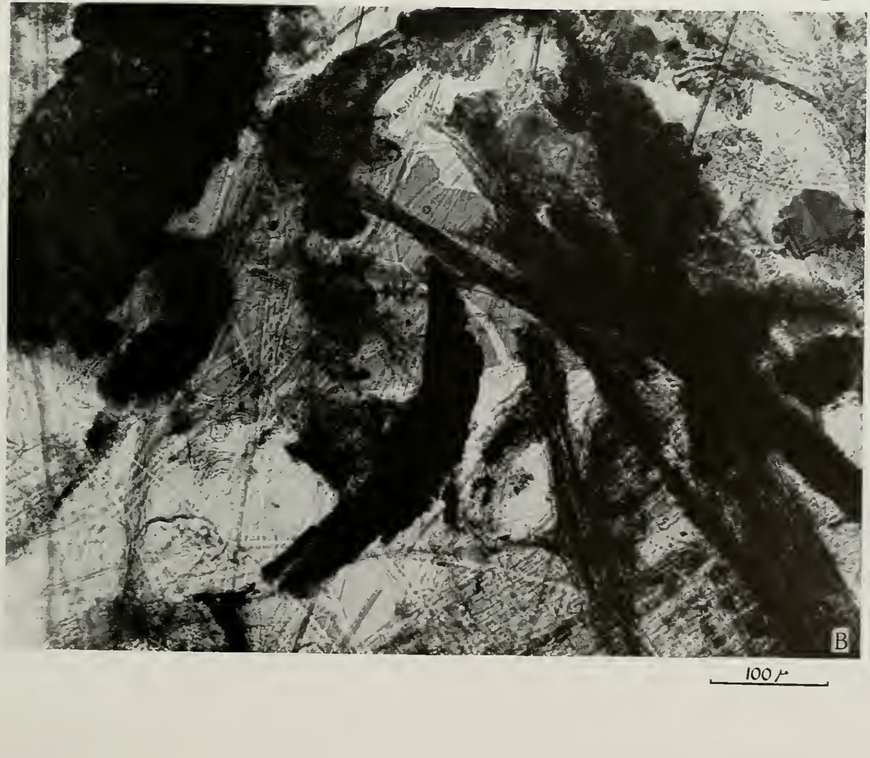
EXPLANATION OF PLATE 15

Louisiana mud from the "thin vegetable soup" zone of figure 27. The mud was spread on coarse filter paper and immediately dried. The fibers of the filter paper are seen in the background.

(A) Sample from Bayou Trépagnier. (B) Sample from Chicot Lagoon.

In both samples there are pieces of totally opaque plant debris along with translucent brown ones. In the upper left corner of figure B there is a piece resembling fusain. The plant debris is flaky, much as in the Mecca and Logan Quarry shales (cf. pl. 10, H and I).

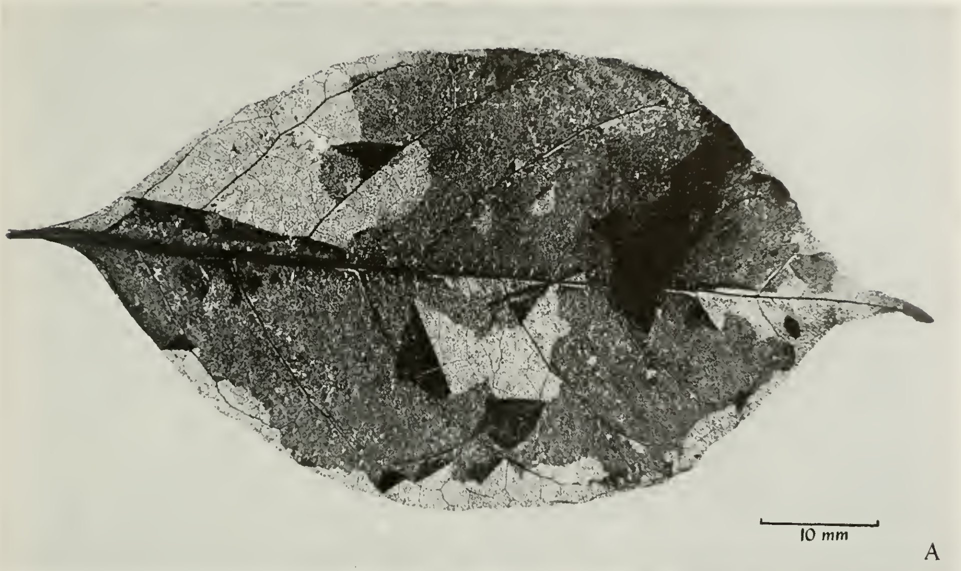

A
100 µ

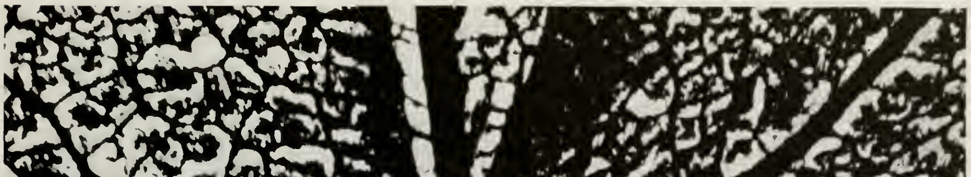

B
100 µ

EXPLANATION OF PLATE 16

(A) A leaf of *Nyssa sylvatica* from the surface water of Bayou Labranche, Louisiana. Much of the tissue has become entirely opaque.

(B) Enlarged portion of the same leaf.


10 mm
A

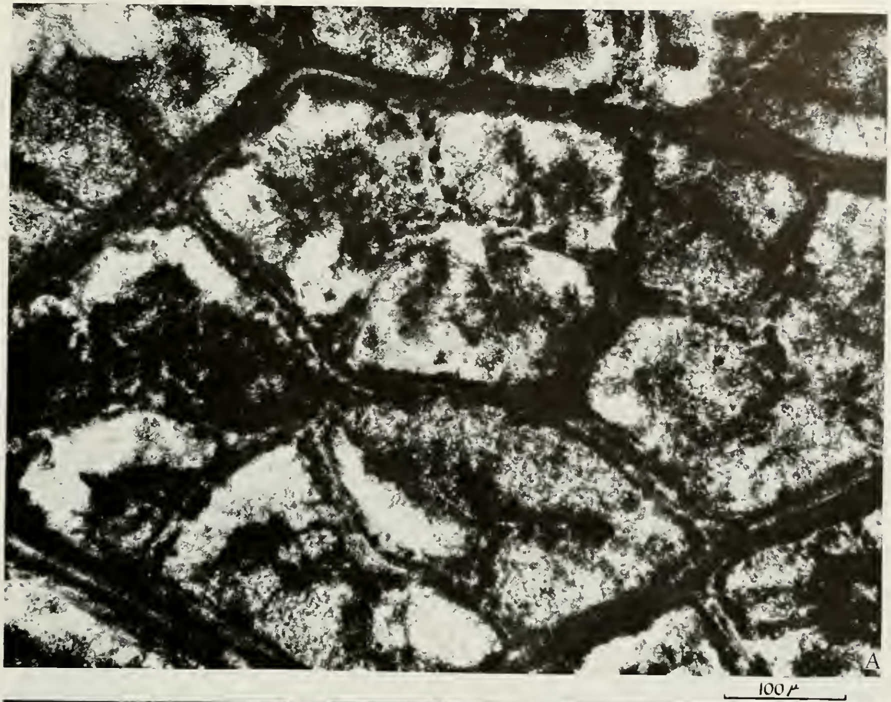

B
1 mm

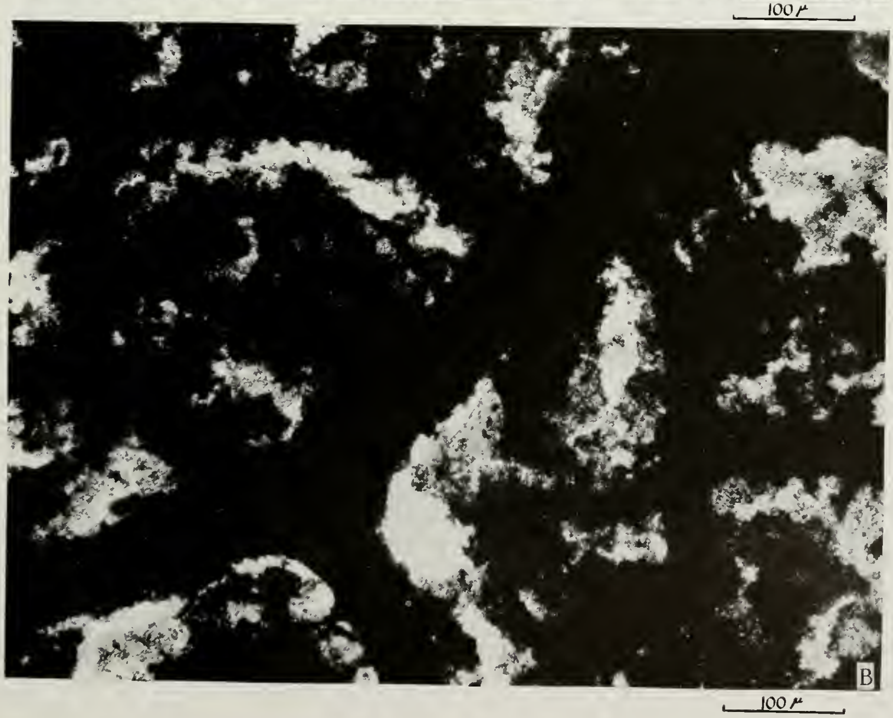
EXPLANATION OF PLATE 17

Much enlarged portions of two partially decomposed leaves from the surface water of Bayou Labranche, Louisiana (seen by transmitted light):

(A) *Salix* sp.; the veinlets have become partially opaque surficially; tissues bounded by veinlets are largely translucent and pale brown in color.

(B) A small portion of a leaf of *Nyssa sylvatica* (same leaf illustrated on pl. 16), very much enlarged to show the irregular outlines of the veinlets, from which opaque flakes have come loose.


A
100 μ


B
100 μ

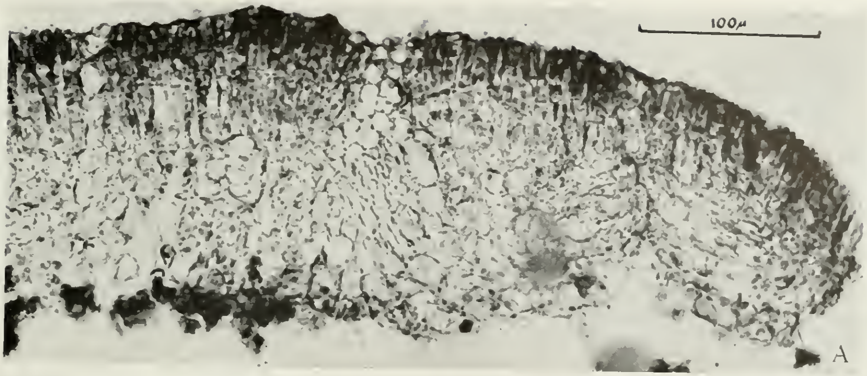
EXPLANATION OF PLATE 18

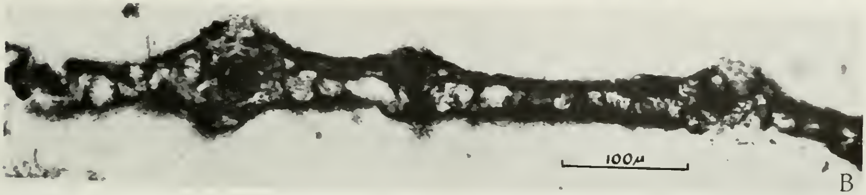
Histological sections of partially degraded leaves from surface water of Bayou Labranche, Louisiana, showing development of opaque substance:

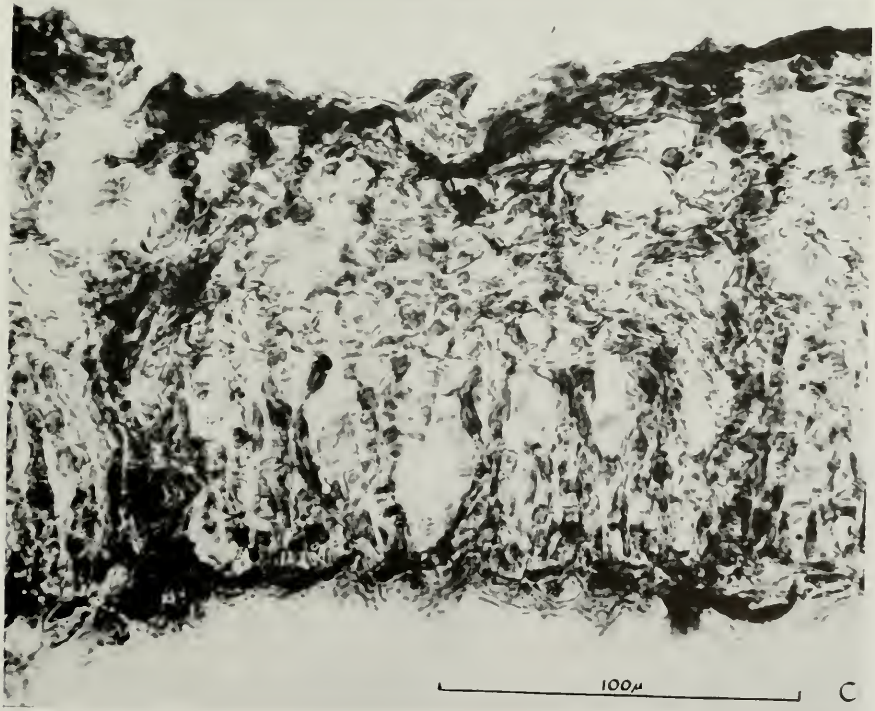
(A) Leaf with good histological detail, but with the surface tissue beginning to become opaque.

(B) Advanced stage of degradation; the thickness of the leaf has been greatly reduced and there is much opaque material, mostly near the surface.

(C) Opaque material beginning to form along vertical strands of tissue in the body of the leaf.


100μ
A


100μ
B


100μ
C

EXPLANATION OF PLATE 19

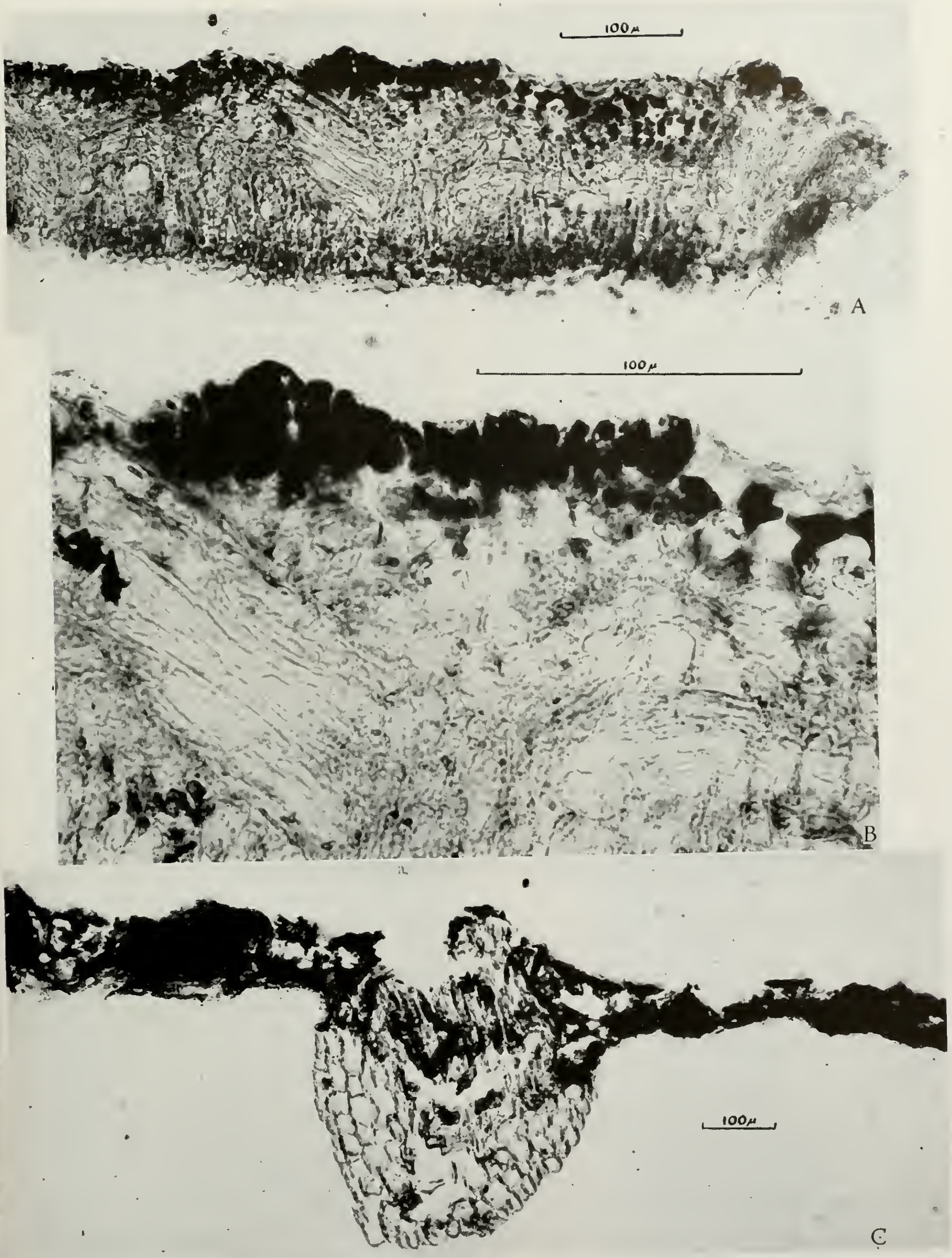
Histological sections of partially degraded leaves from surface water of Bayou Labranche, Louisiana, showing development of opaque substance:

(A) Leaf with opaque substance near the surface, apparently formed within individual cells.

(B) Close-up of the same section, in which two guard cells are visible on the upper right side of the picture. The cell walls of these cells are not opaque, but the cell contents are.

(C) Leaf in advanced state of decomposition, showing the flaky nature of the opaque substance; the vein has not become opaque.

Plate 19


100μ
A
100μ
B
100μ
C

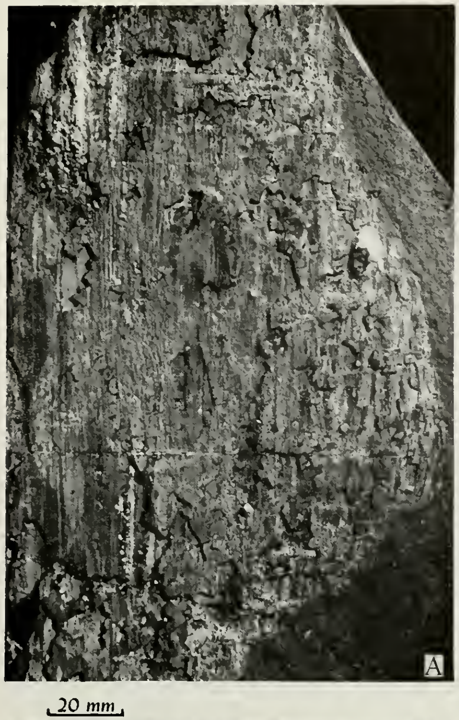
EXPLANATION OF PLATE 20

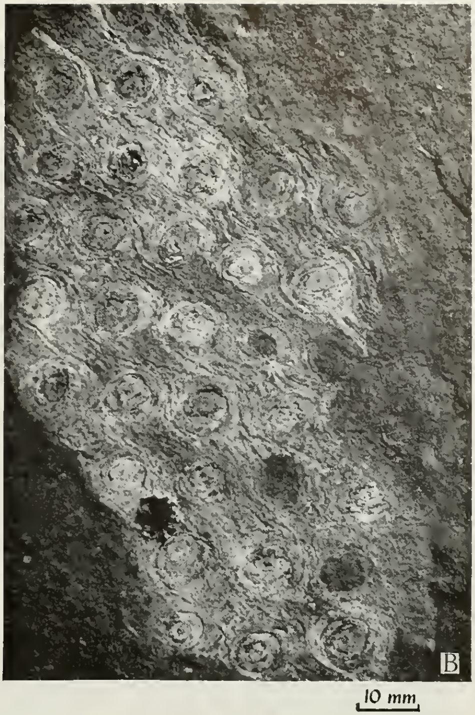
(A) Typical preservation of a piece of driftwood in the Mecca Quarry shale, Mecca Quarry, level B2.4, PP 16375; the surface shows longitudinal striations, and the substance has typical coaly cleavage; in thin section the substance is bright orange, indistinguishable from anthraxylon.

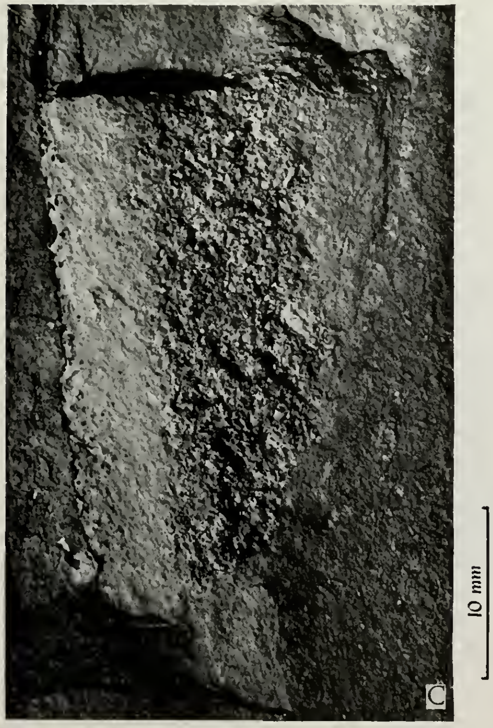
(B) A piece of *Omphalophloios cyclostigma*, Mecca Quarry shale, Mecca Quarry, level B4.1, PP 16376; this was the only specifically determinable piece of wood in the Mecca Quarry sample. It is preserved as a thin layer of anthraxylon on a bedding plane.

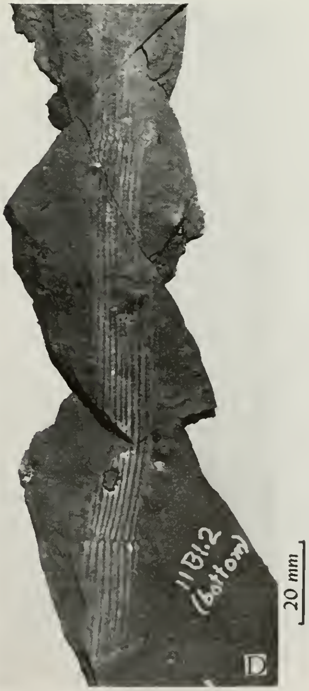
(C) A portion of a snail burrow in the Mecca Quarry shale, Mecca Quarry, level A3.1/.2, PE 8014, seen from beneath and showing trail of concentrated fecal material.

(D) Stem of *Calamites* sp., Mecca Quarry shale, Mecca Quarry, level B1.2, PP 16377. The substance is reduced to a mere film.


A
20 mm


B
10 mm


C
10 mm

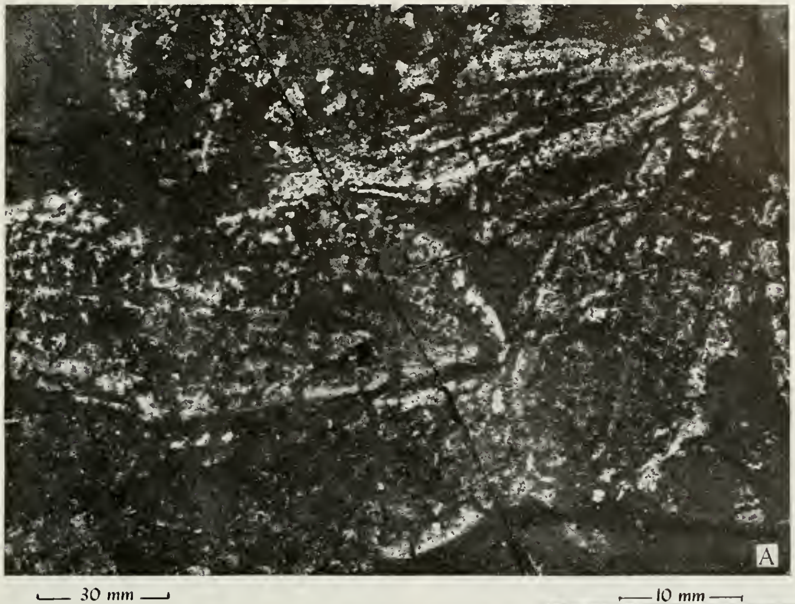

11Bl.2
(bottom)
20 mm
D

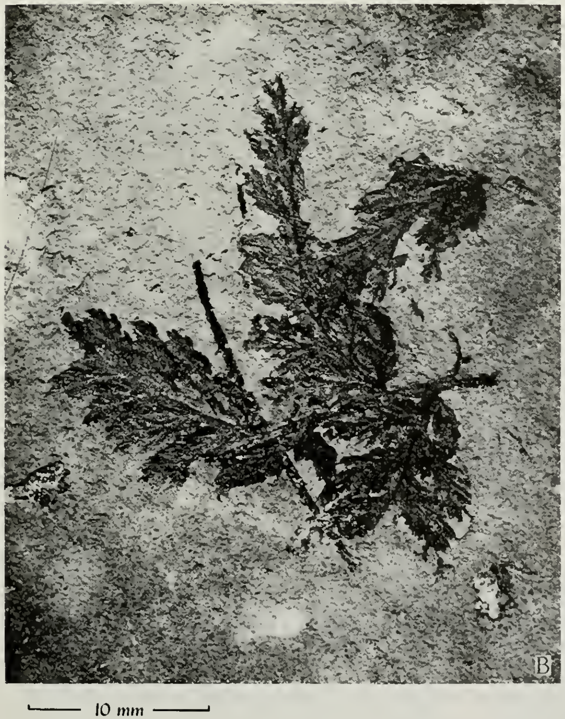
EXPLANATION OF PLATE 21

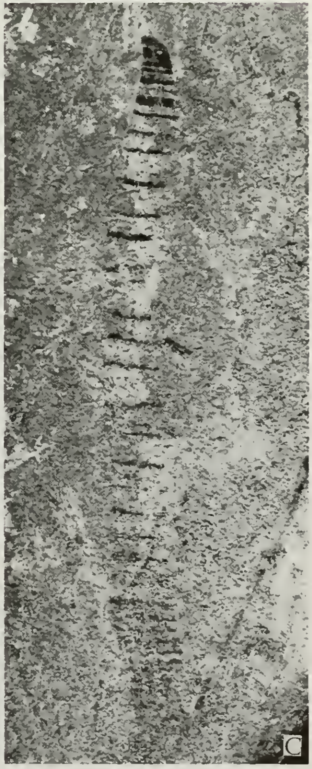
(A) Unknown fossils, Mecca Quarry shale, Mecca Quarry, level A3.4, PP 16378, provisionally interpreted as sea weeds. They are light brown markings on the shale bedding surfaces.

(B) *Sphenopteris* sp. pinnules. Logan Quarry shale, Garrard Quarry, Zone 6 (humulite), PP 16379.

(C) Impression of the bristle rows of an oligochaete worm on a bedding surface of Mecca Quarry shale, Mecca Quarry, level A1.4, PE 8001.


A
30 mm


B
10 mm


10 mm
C

EXPLANATION OF PLATE 22

(A) *Concavicaris sinuata* (Meek and Worthen). Mecca Quarry shale, Mecca Quarry, level A3.4, PE 7097. The two valves of the carapace are superposed, slightly off register.

(B) *Concavicaris sinuata,* finely fragmented, very probably mouthed by a predator. Mecca Quarry shale, Mecca Quarry, level A3.4, PE 8003.

(C) *Concavicaris sinuata,* a bitten specimen. Mecca Quarry shale, Mecca Quarry, level A3.4, PE 8004.

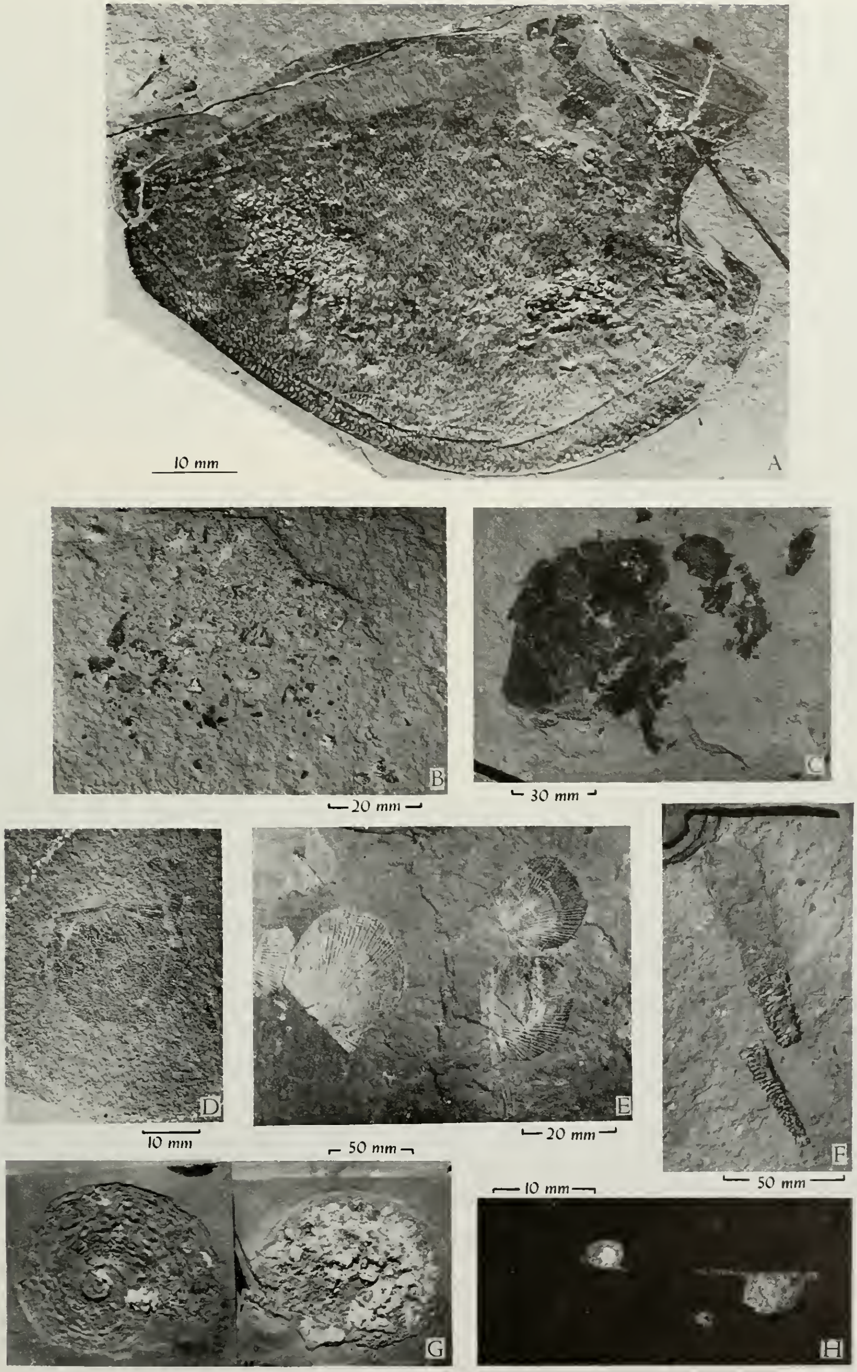
(D) *Dunbarella* sp., impression of decalcified(?) shell. Mecca Quarry shale, Mecca Quarry, level D, PE 8005.

(E) *Dunbarella* sp., impressions of shells, one with both valves together. Logan Quarry shale, *Dunbarella* zone, Haworth Creek, PE 8006.

(F) *Pseudorthoceras knoxense* (McChesney), impression of bitten phragmocone and flattened living chamber. Mecca Quarry shale, Mecca Quarry, level A3.3, PE 8007.

(G) Goniatite, plate and counterplate. Logan Quarry shale, Logan Quarry, level G, PE 8008. Space between shell impressions filled with heavy calcite.

(H) *Pteria* sp. Posterior part of shell, except for hinge, presumably dissolved prior to burial. Logan Quarry shale, *Dunbarella* zone, Haworth Creek, PE 8009.


10 mm
A
B
— 20 mm —
C
— 30 mm —
D
10 mm
— 50 mm —
E
— 20 mm —
F
— 50 mm —
G
— 10 mm —
H

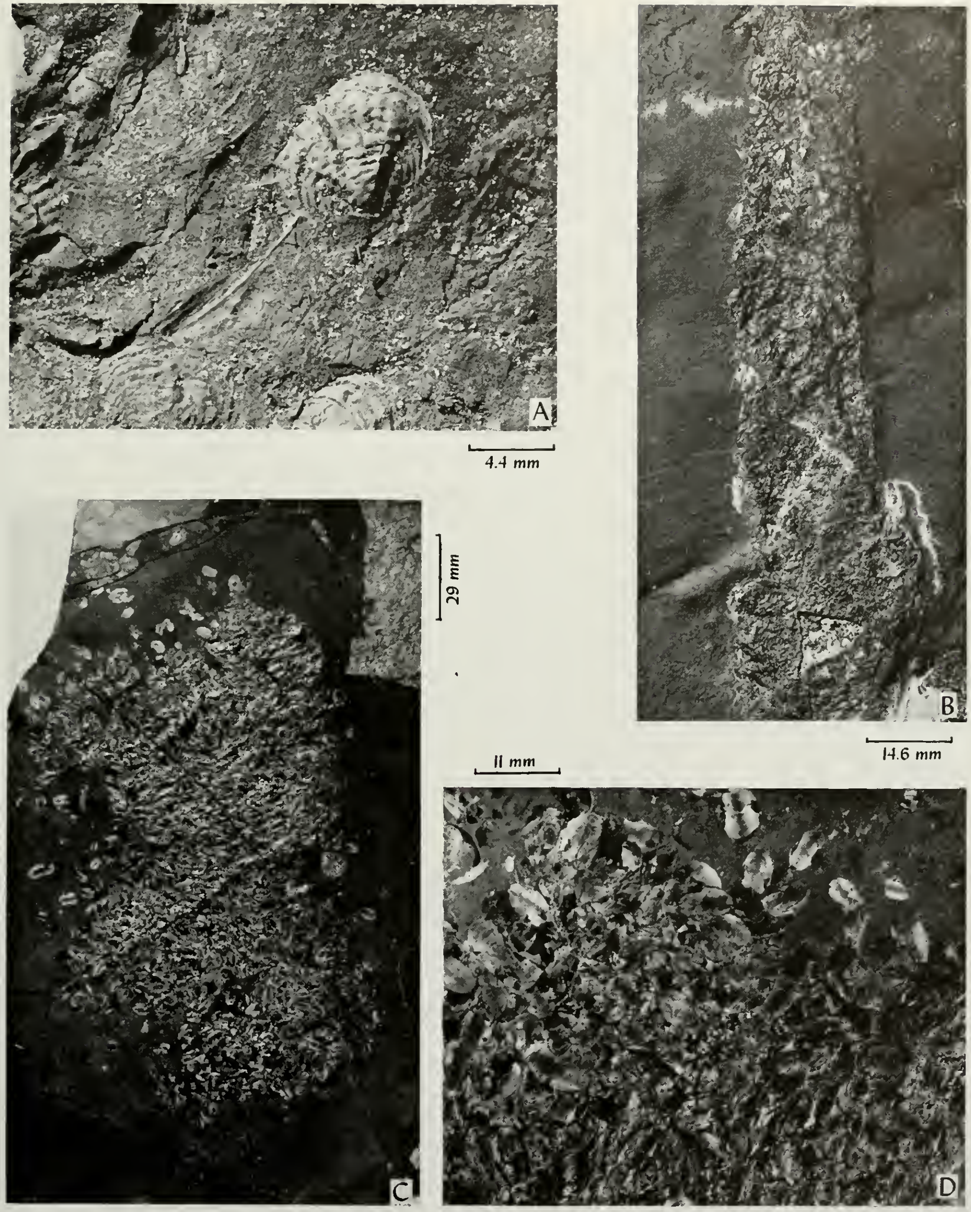
EXPLANATION OF PLATE 23

(A) *Desmoinesia muricatina* (Norwood and Pratten), with unbroken spines. Mecca Quarry shale, channel clod, West Montezuma, PE 8010.

(B) Longitudinal tract of minced *Myalina* debris, presumably the work of a predator. Logan Quarry shale, Garrard Quarry, Zone 4 (humulite), PE 8011.

(C) Large aggregation of shells (*Lingula* sp.) preserved in original material, some showing color pattern. Logan Quarry shale, Garrard Quarry, Zone 6 (humulite), PE 8012.

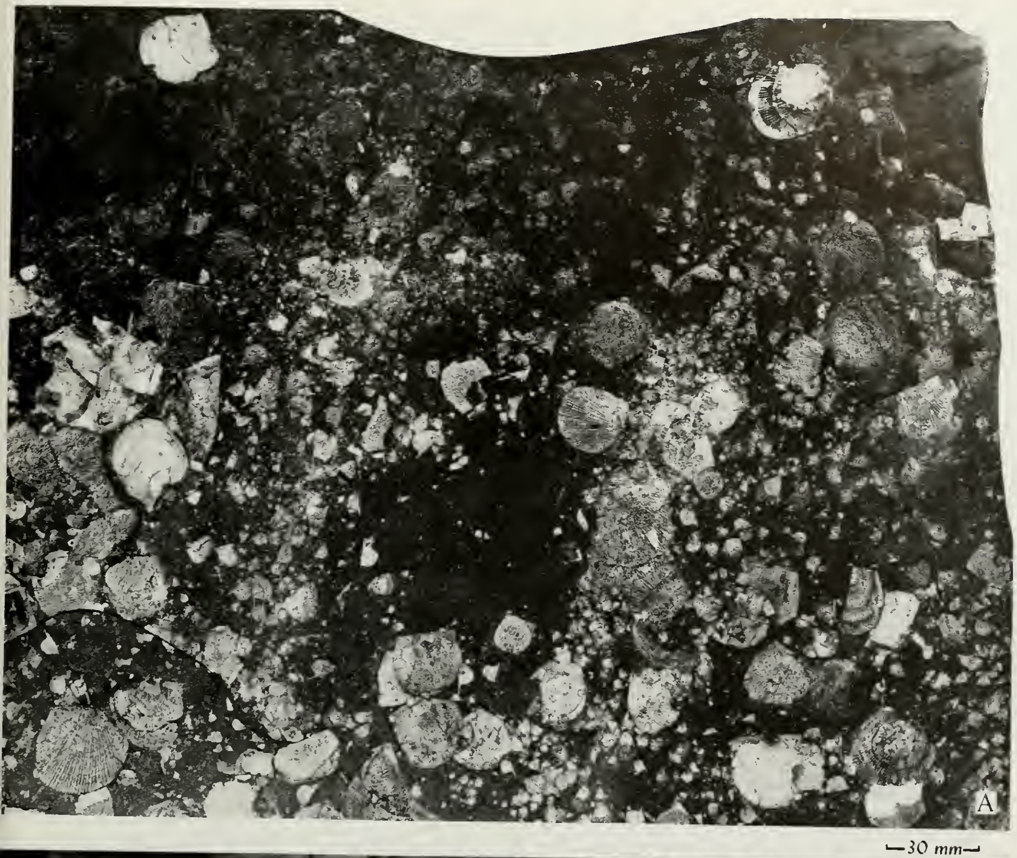
(D) Detail of same group of *Lingula*.

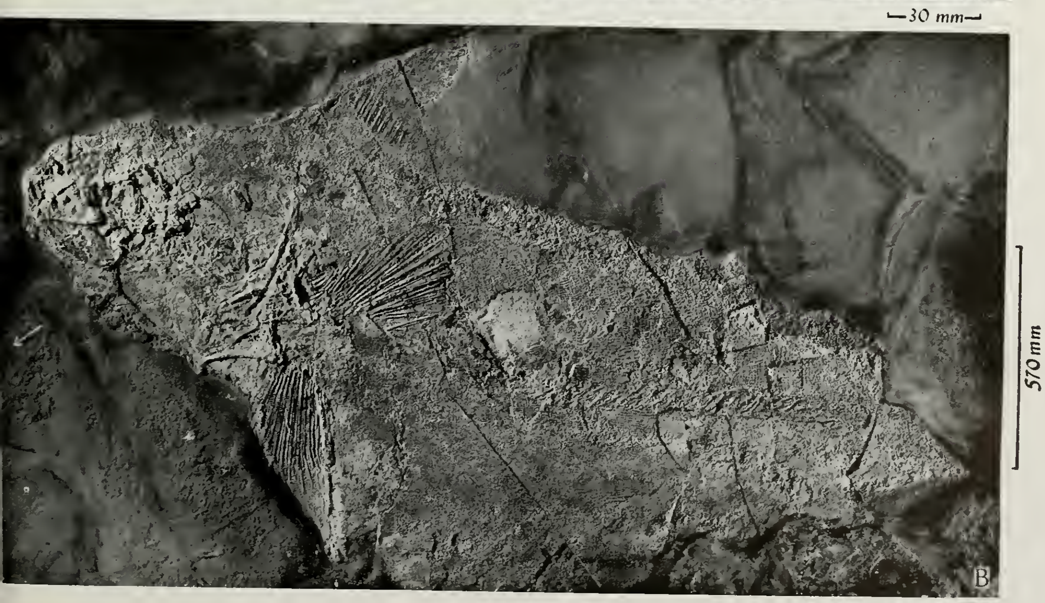

A
4.4 mm
B
14.6 mm
29 mm
C
11 mm
D

EXPLANATION OF PLATE 24

(A) *Dunbarella* and *Pteria* shells on a piece of Logan Quarry black shale from Big Pond Creek, PE 8013. The smaller shells and shell fragments tend to be aligned in broad rows. Many of the casts of *Dunbarella* are filled with thick calcite discs.

(B) A large shark from Logan Quarry shale at Logan Quarry, level J, PF 2201. The skin is preserved in place except for skin rolls that formed on the sides of the specimen. The calcified cartilage skeleton is nearly undisturbed. The skeleton was directly covered by the black band in level J. Arrow indicates north.

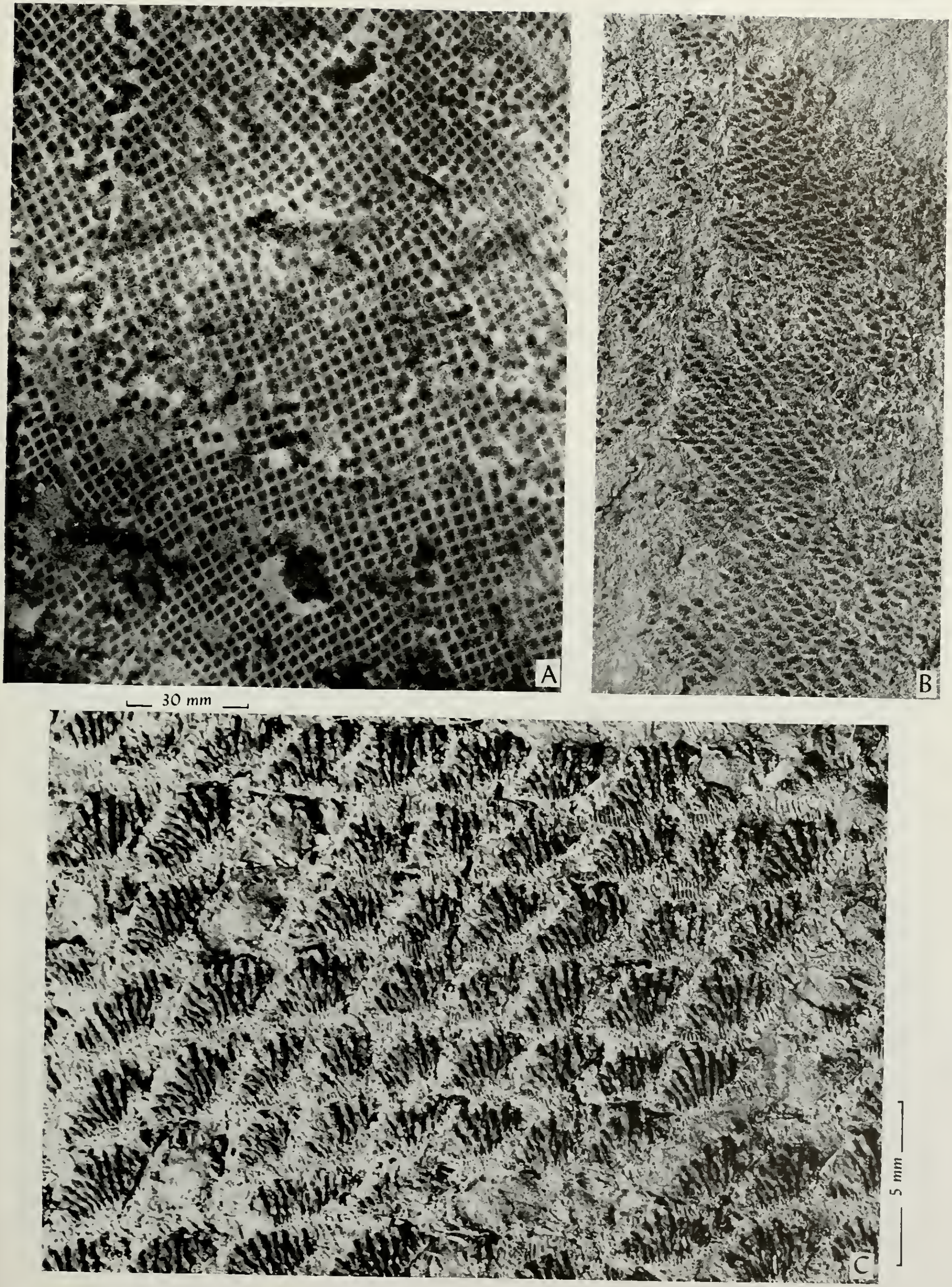

A
30 mm


570 mm
B

EXPLANATION OF PLATE 25

Detail of the shagreen of the large shark (PF 2201) as seen in the same magnification on X-ray (A) and photograph (B); and with additional enlargement (C).

Plate 25

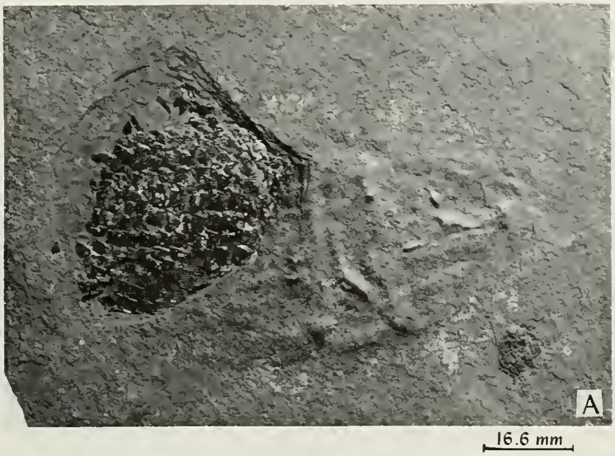

A
B
30 mm
5 mm
C

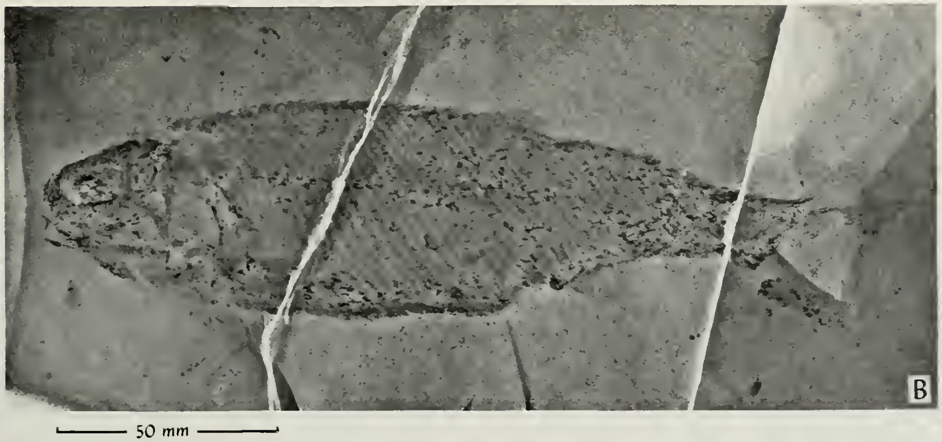
EXPLANATION OF PLATE 26

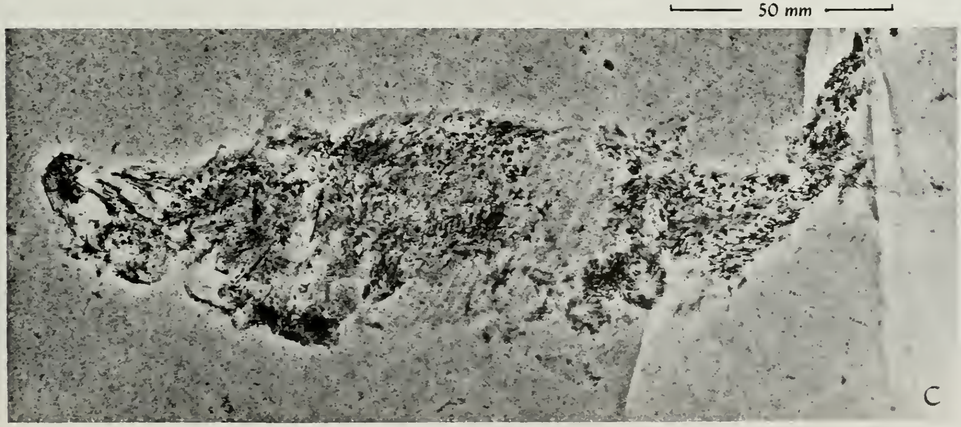
(A) A palaeoniscoid fish with the posterior portion bitten off. The skull lies beneath a thin layer of shale. Logan Quarry shale, Logan Quarry, level J, PF 2644.

(B) Radiograph of a near-perfectly preserved palaeoniscoid. The tail fin was bitten into, but not completely severed. Logan Quarry shale, Logan Quarry, level J, PF 2275.

(C) Radiograph of a palaeoniscoid, showing two sets of bite marks. Logan Quarry shale, Logan Quarry, level J, PF 2247.


A
16.6 mm

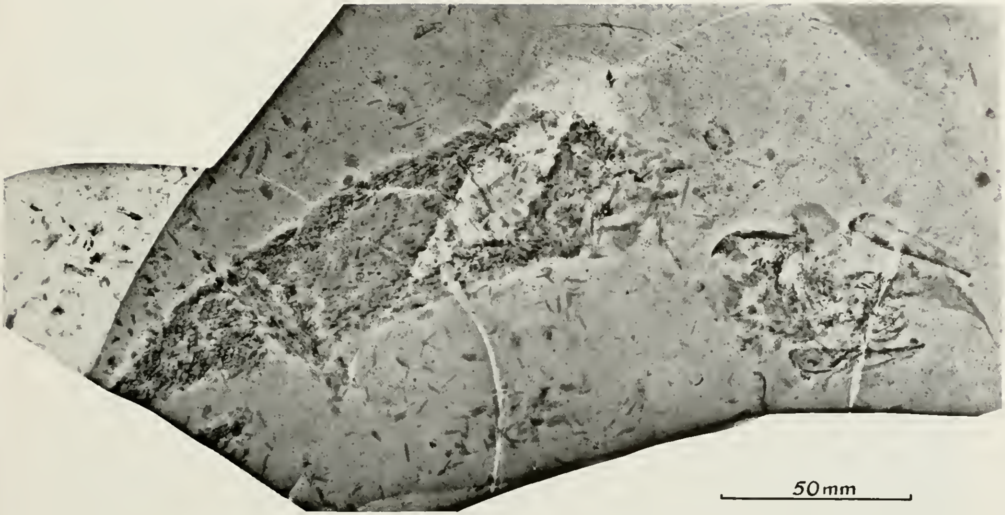

B
50 mm

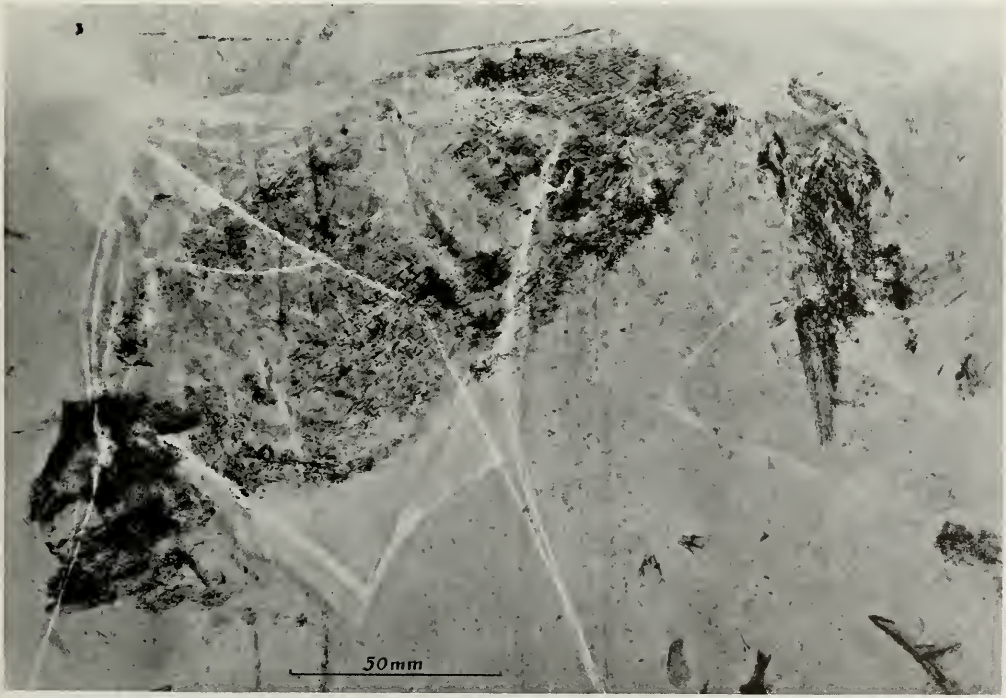

50 mm
C

EXPLANATION OF PLATE 27

(A) Radiograph of a palaeoniscoid with one bite mark across the body, and another almost entirely severing the head. Logan Quarry shale, Logan Quarry, level J, PF 2255.

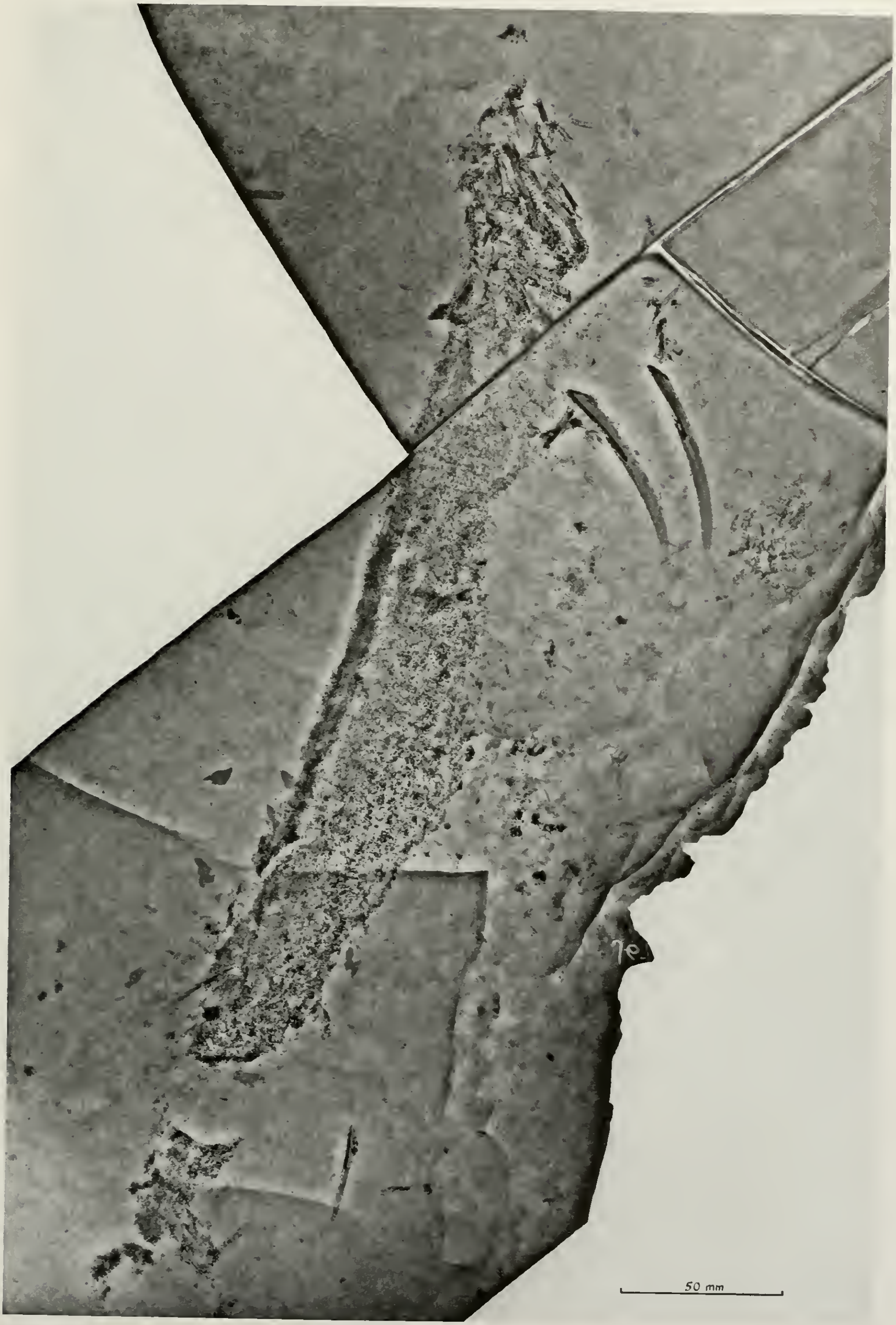
(B) Radiograph of a palaeoniscoid with the tail region almost but not completely severed. Another bite injury is seen in the head region. Logan Quarry shale, Logan Quarry, level J, PF 2272.


50mm


50mm

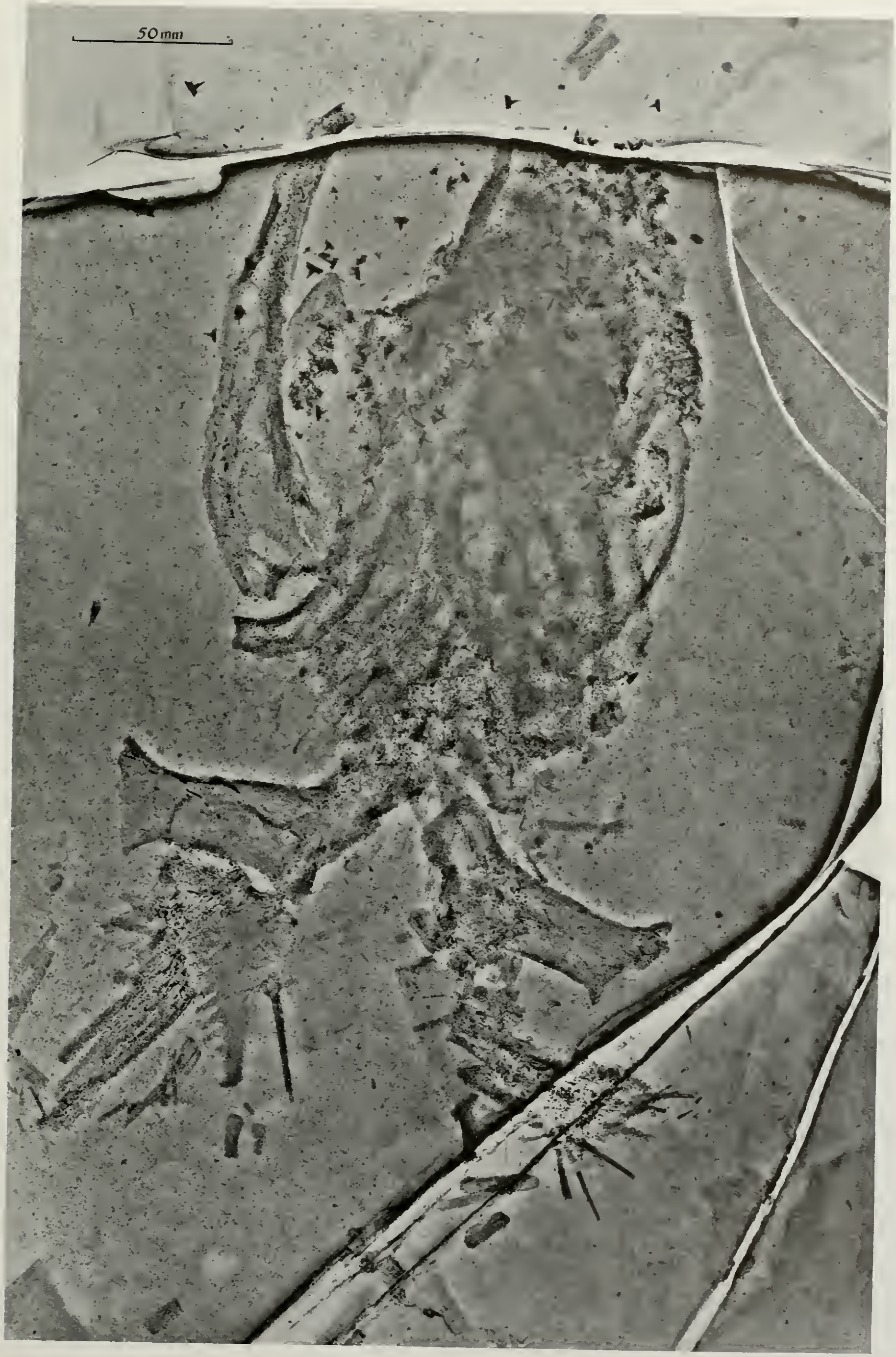
EXPLANATION OF PLATE 28

Radiograph of an acanthodian (probably *Acanthodes* sp.) with the posterior portion of the body bitten off. The missing piece near the bitten end adhered to the counterplate; it was not bitten off. Logan Quarry shale, Logan Quarry, level J, PF 2407.


50 mm

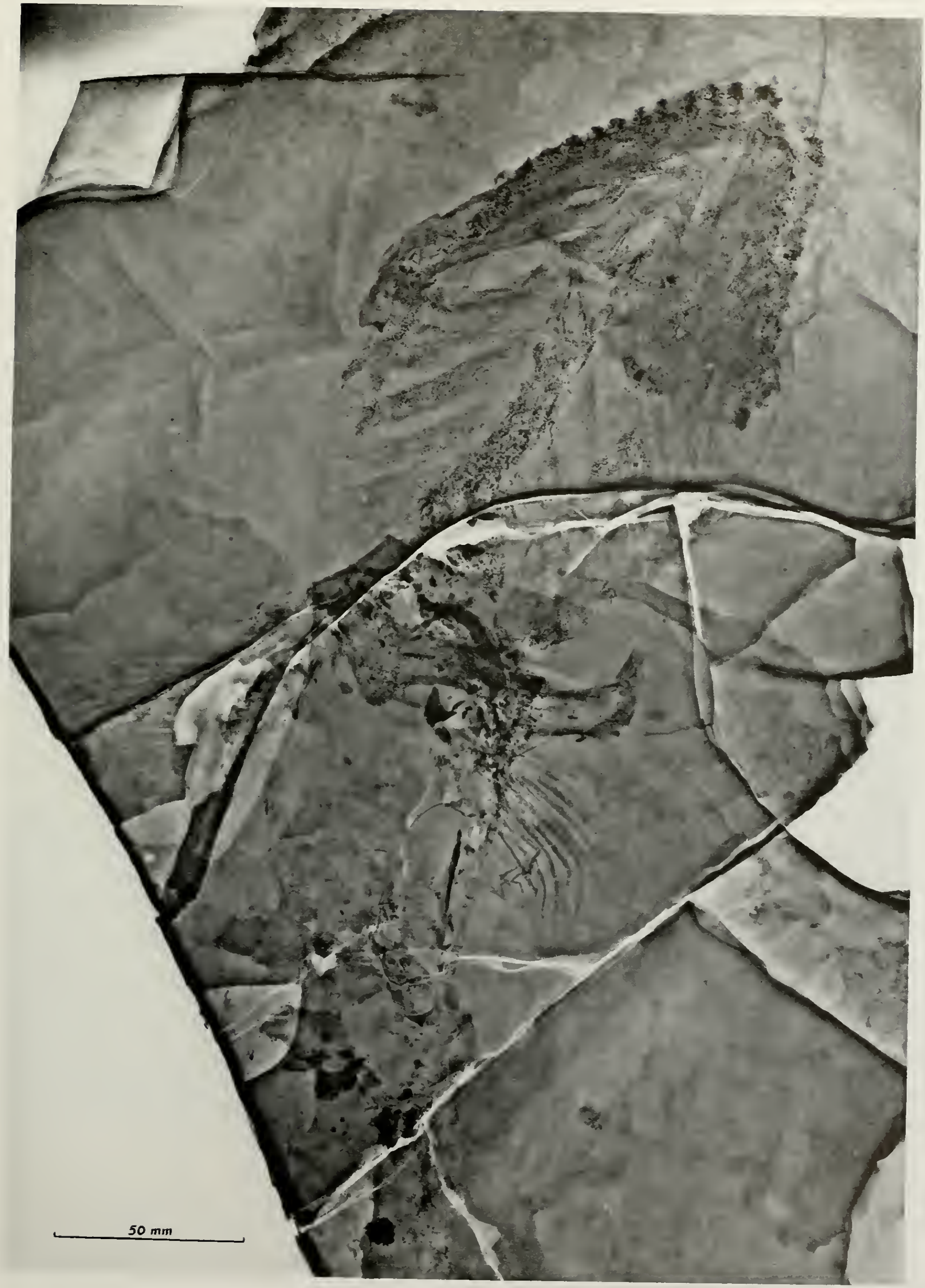
EXPLANATION OF PLATE 29

Radiograph of a cladodontid shark, in dorso-ventral position. The snout, one of the Meckel's cartilages, and most of the body are bitten off. Logan Quarry shale, Logan Quarry, level G, PF 2448.


50 mm

EXPLANATION OF PLATE 30

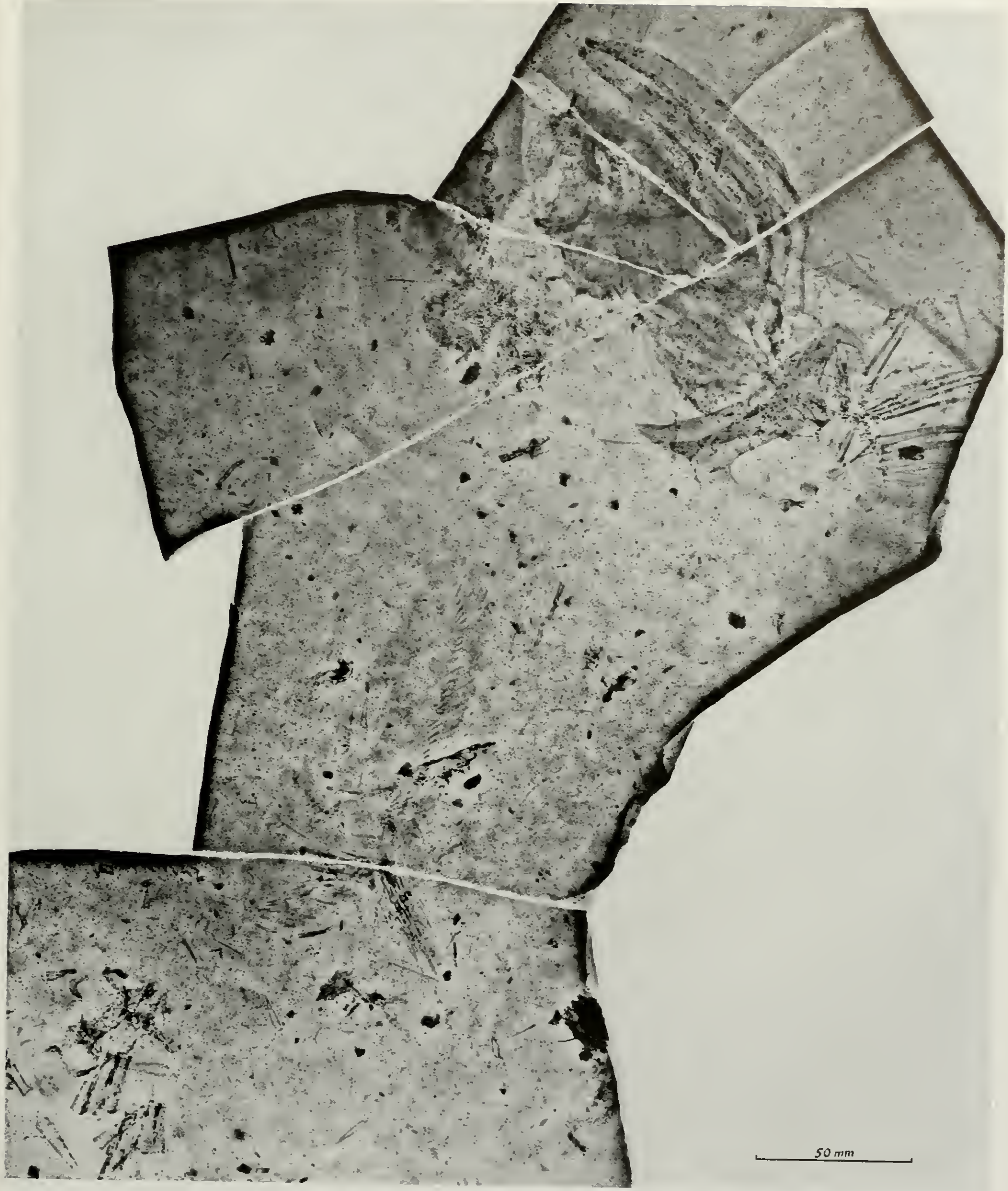
Radiograph of a shark in dorso-ventral position. Most of the body and the Meckel's cartilages are missing. The type of mutilation is almost identical with that of the specimen shown in plate 29. Logan Quarry shale, Logan Quarry, level G, PF 2428.



50 mm

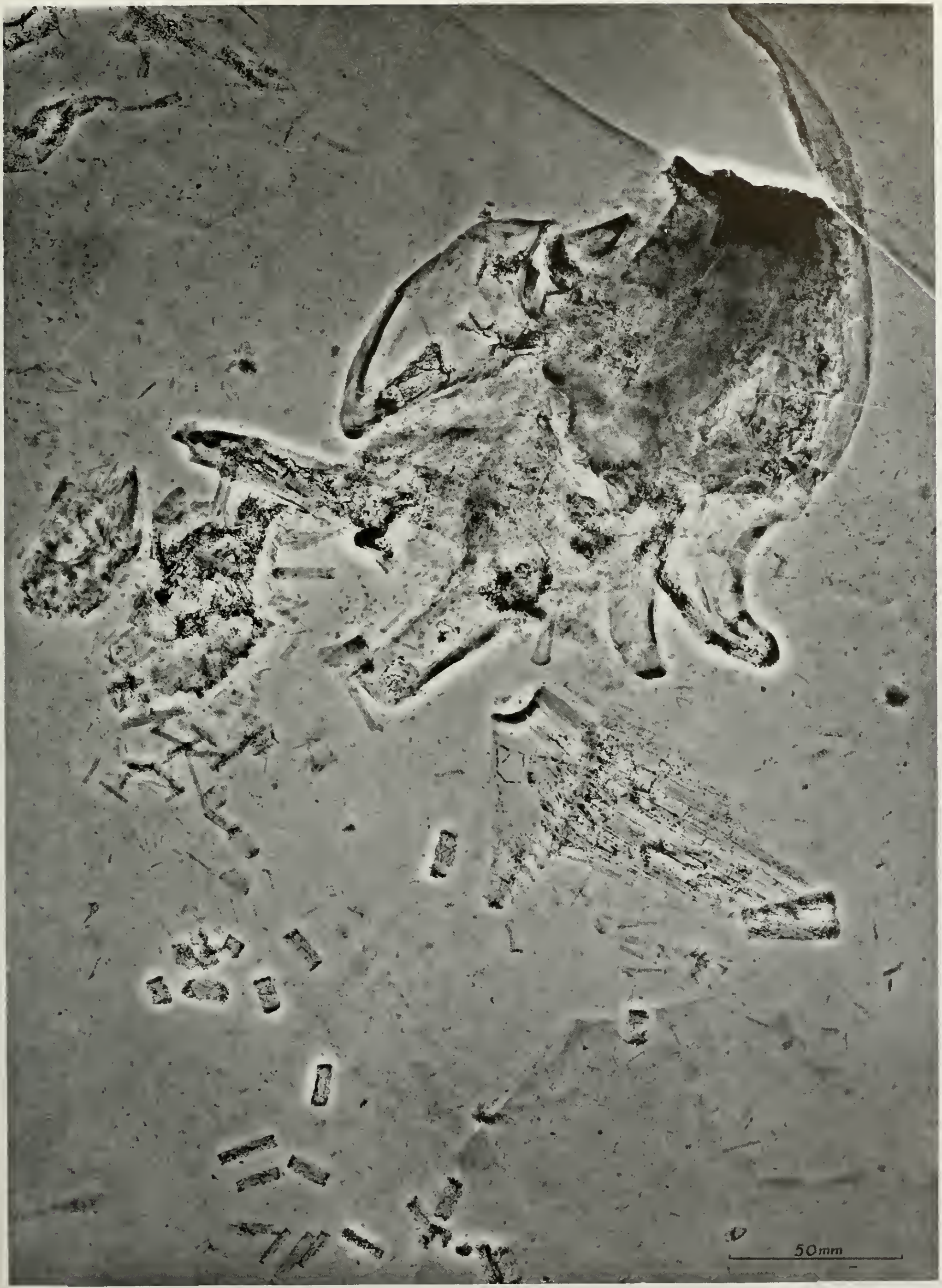
EXPLANATION OF PLATE 31

Radiograph of a shark in lateral position. The vertebral column is severed from the back of the skull, and the posterior part of the skeleton was mouthed. Logan Quarry shale, Logan Quarry, level J, PF 2483.


50 mm

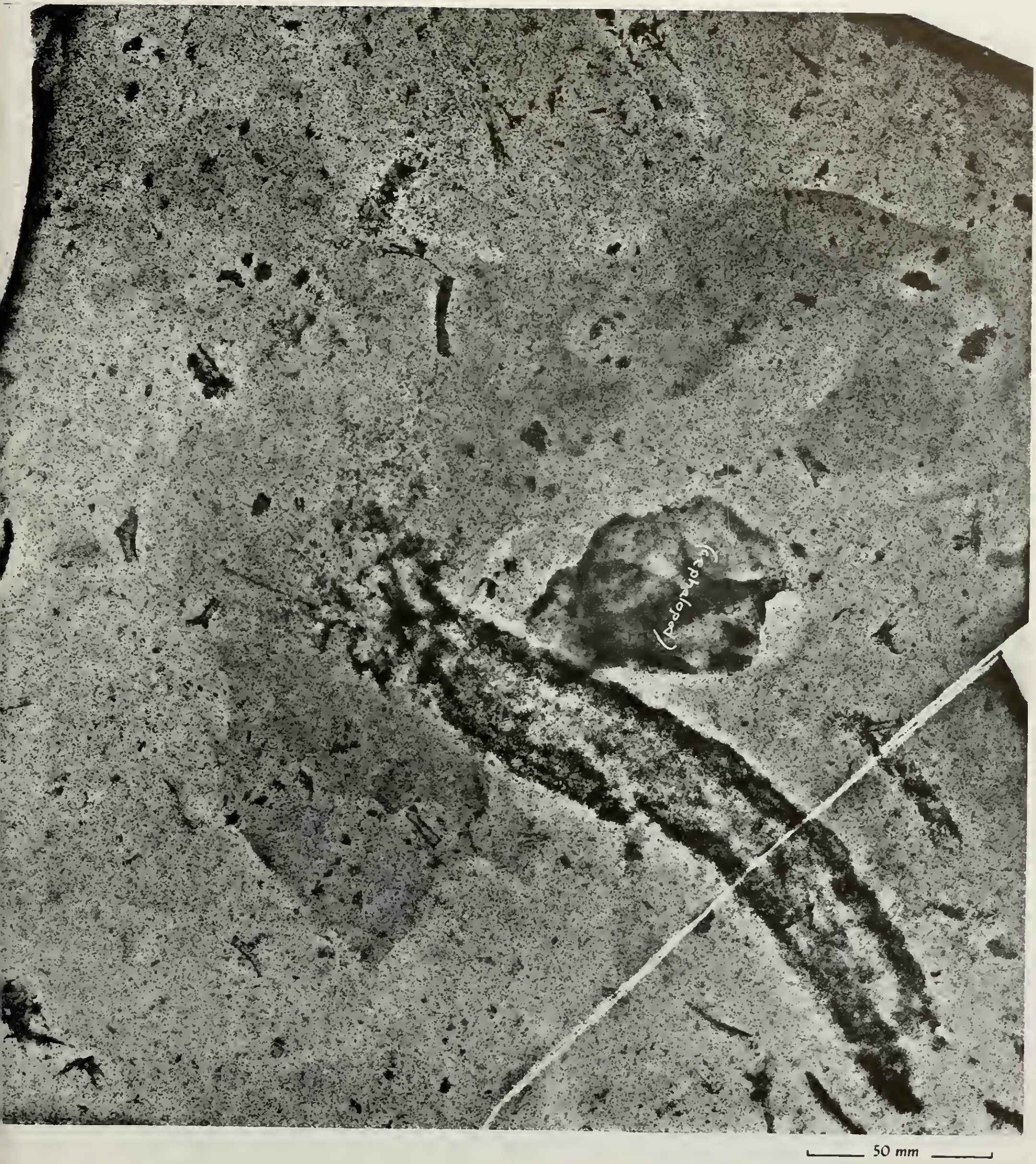
EXPLANATION OF PLATE 32

Radiograph of a cladodontid shark in dorso-ventral position. The left side of the skull, the left shoulder girdle, and the pectoral fin are severely injured, but the right side of the specimen is essentially intact. Logan Quarry shale, Logan Quarry, level J, PF 2624.


50mm

EXPLANATION OF PLATE 33

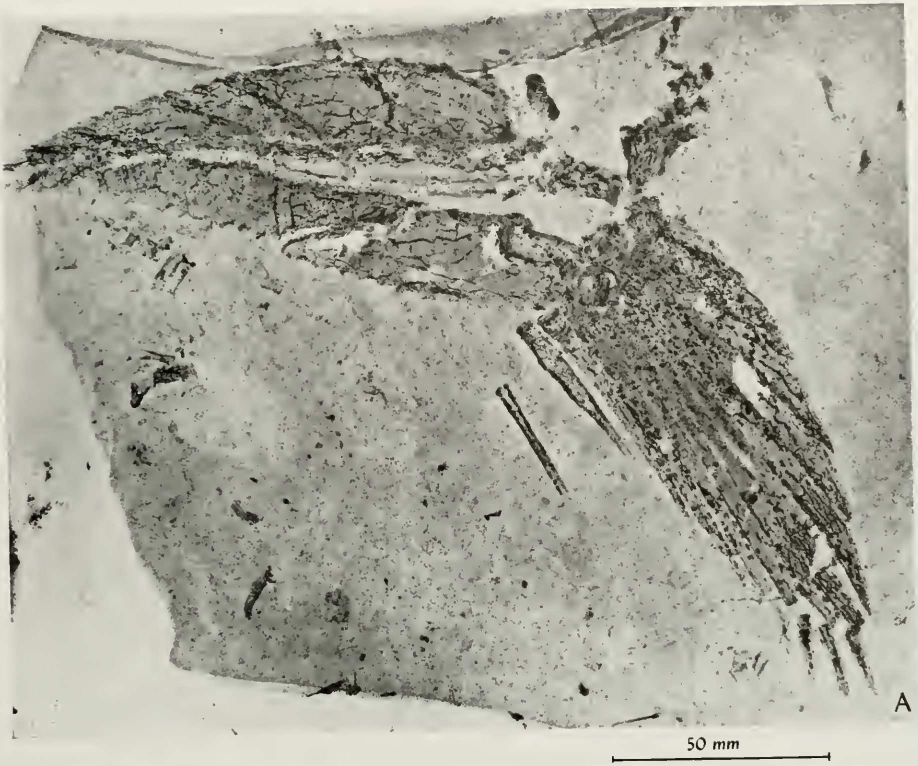
Radiograph of a portion of the body of an acanthodian; note scattering of scales at the site of one of the wounds. Most of the acanthodian specimens are pieces of the body that have been bitten off. Logan Quarry shale, Logan Quarry, level J, PF 2397.

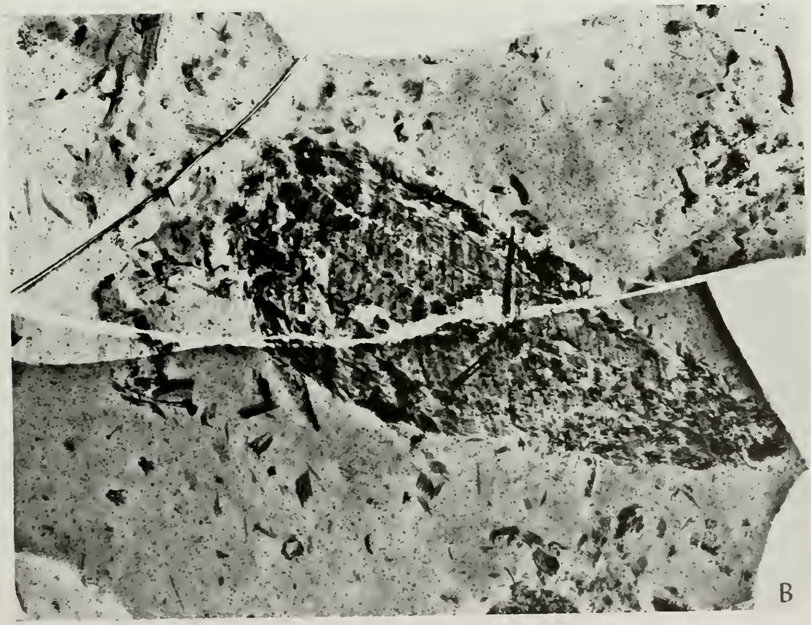

(cephalopod)
50 mm

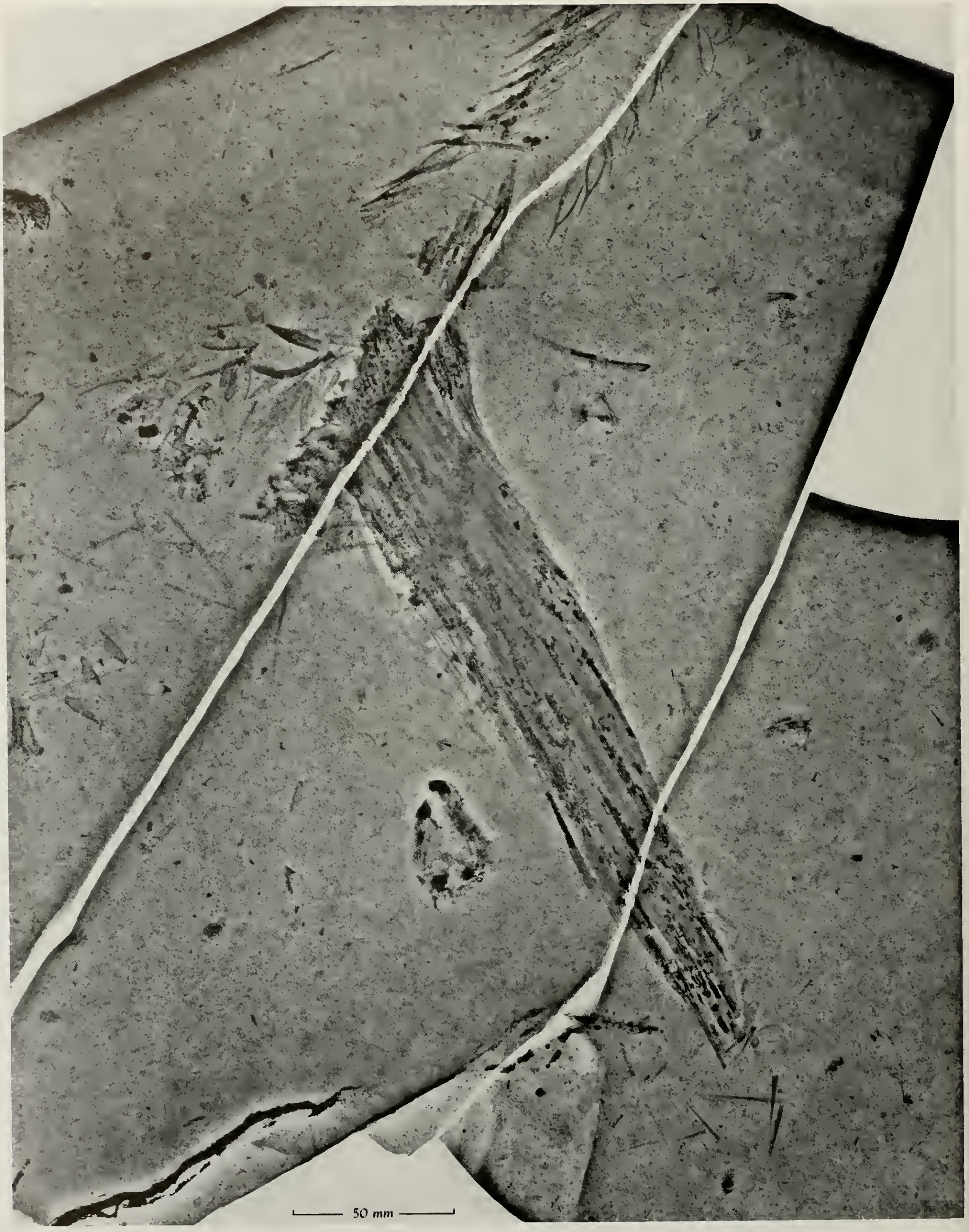
EXPLANATION OF PLATE 34

(A) Radiograph of a bitten-off tail fin of a shark. Logan Quarry shale, Logan Quarry, level J, PF 2566.

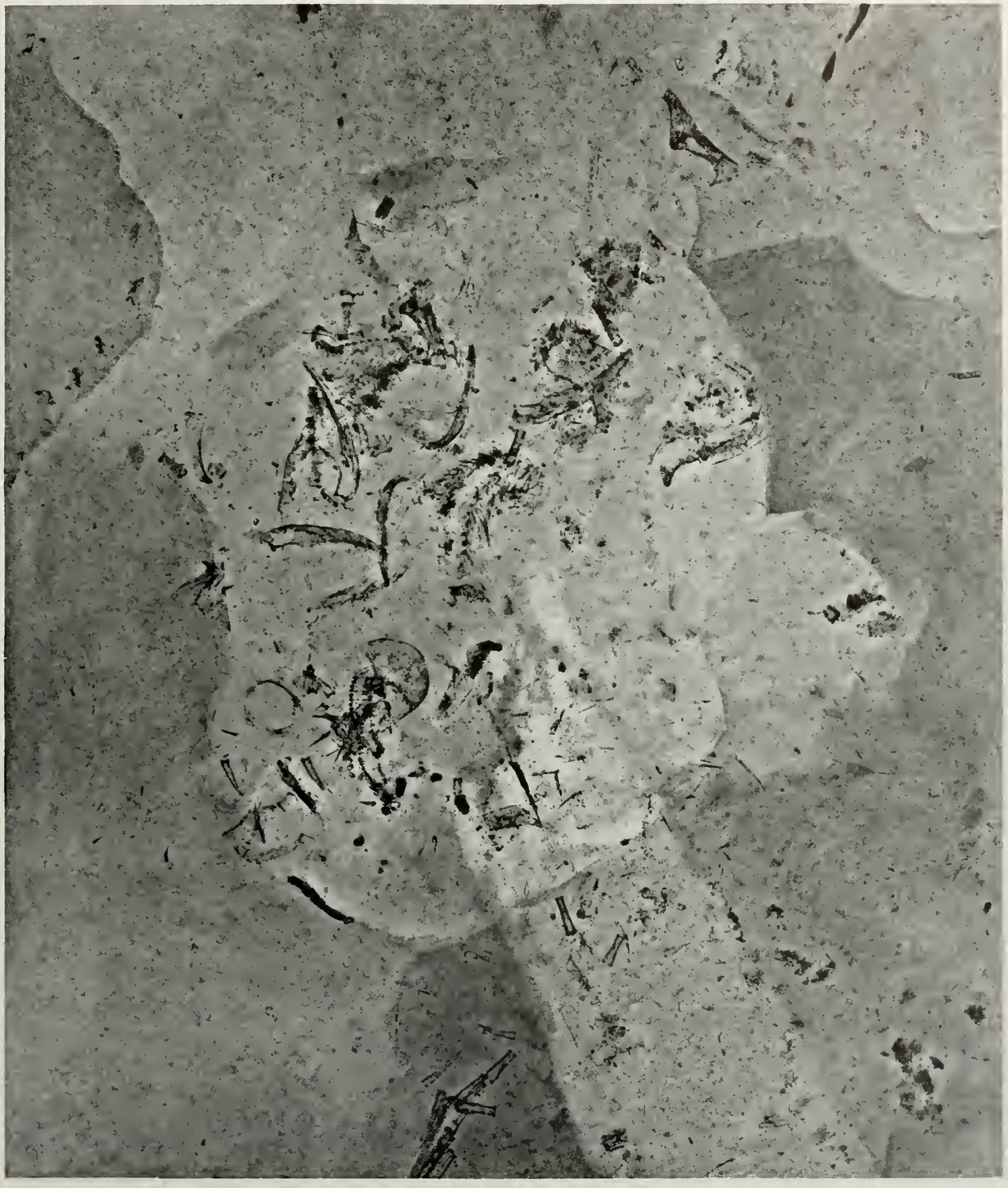
(B) Radiograph of a palaeoniscoid torso; both head and tail have been bitten off. Logan Quarry shale, Logan Quarry, level J, PF 2252.


A
50 mm


B



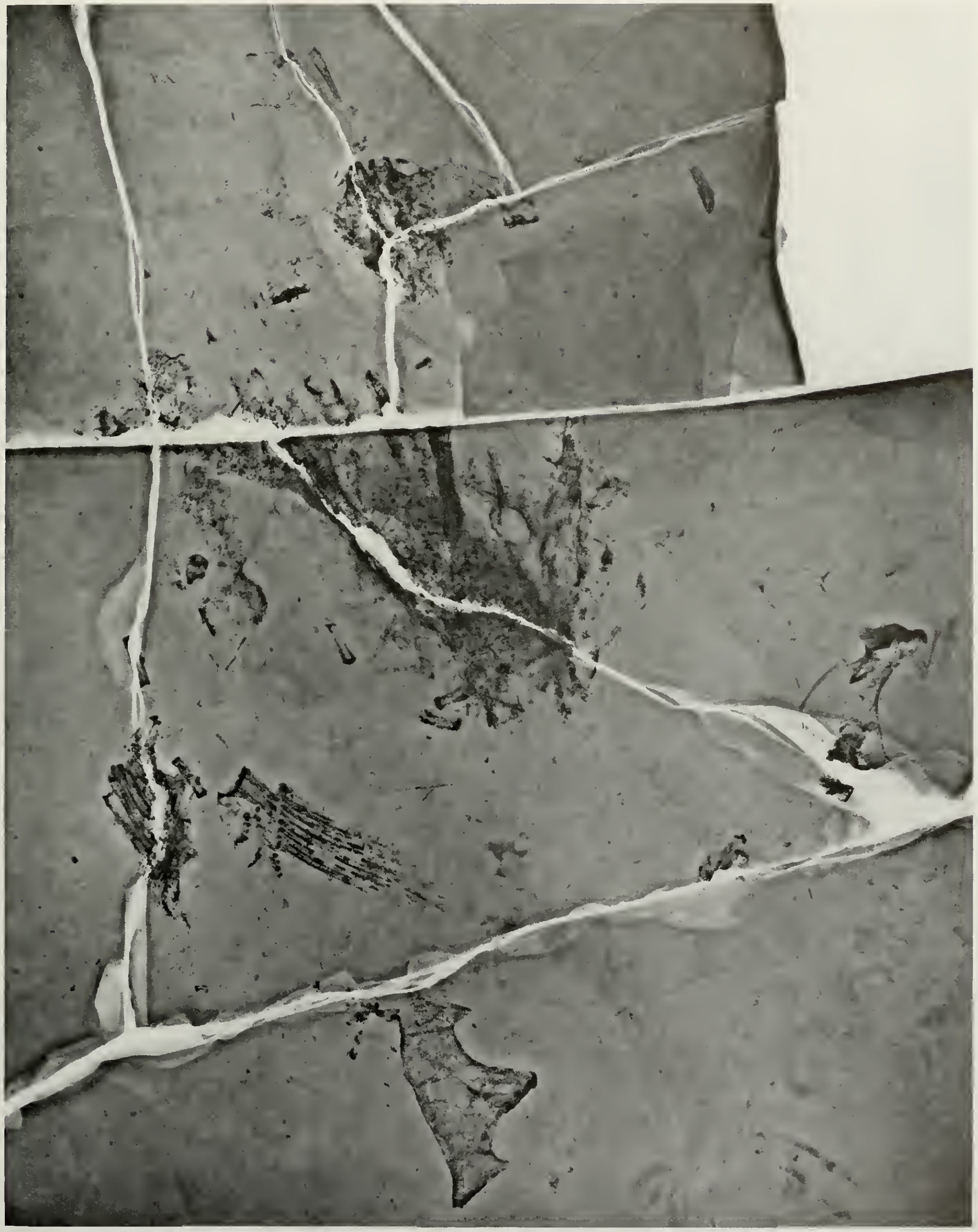
Radiograph of a tail fin of a shark. The dorsal lobe of the fin has been bitten off. Logan Quarry shale, Logan Quarry, level J, PF 2579.



Radiograph of the mouthed remains of a small cladodontid shark. Note articulated parts of the skeleton amid the overall scatter. Logan Quarry shale, Logan Quarry, level J, PF 2527.

EXPLANATION OF PLATE 37

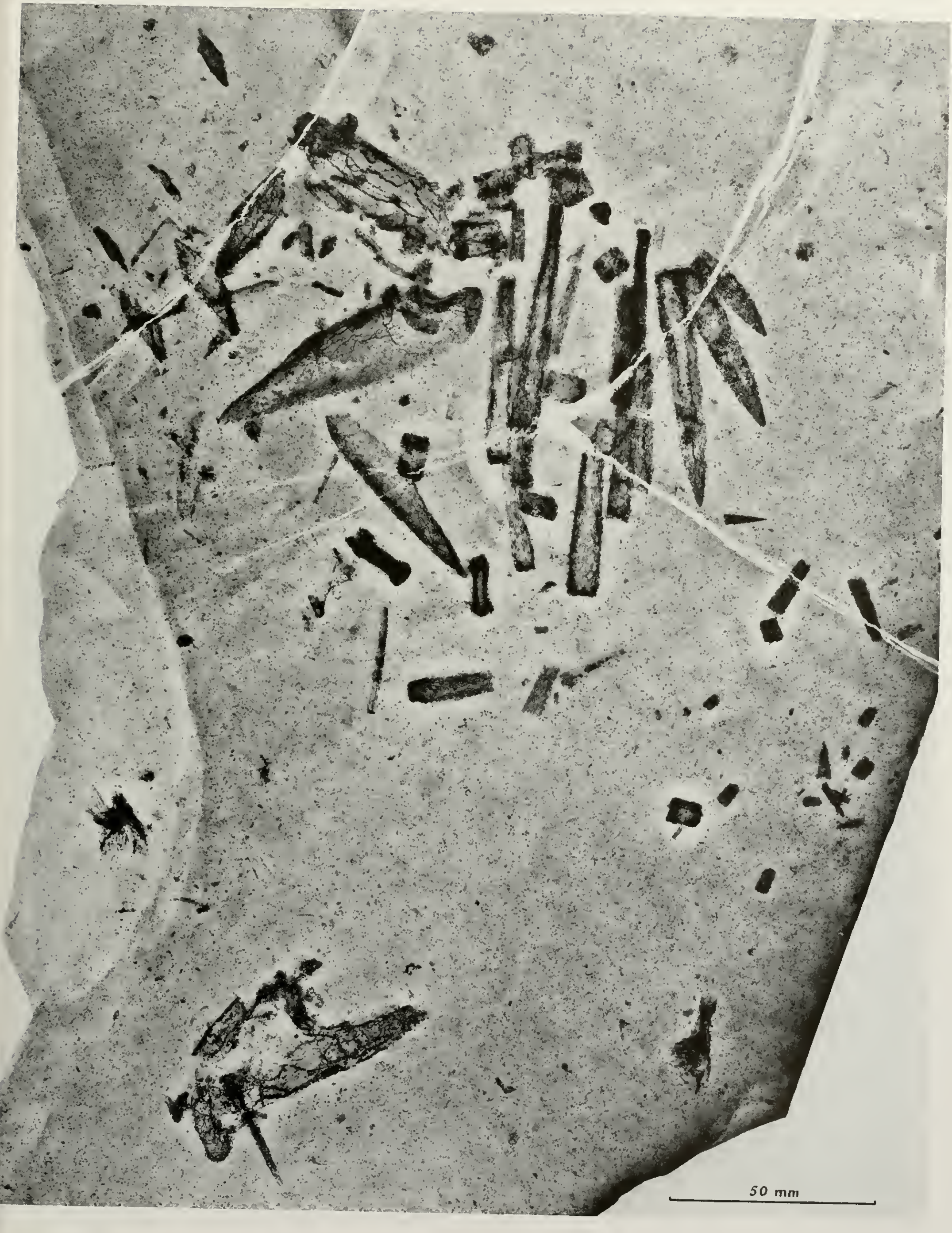
Radiograph of the chewed remains of a shark head along with an articulated fin and unbroken girdle elements. Logan Quarry shale, Logan Quarry, level J, PF 2495.



50 mm

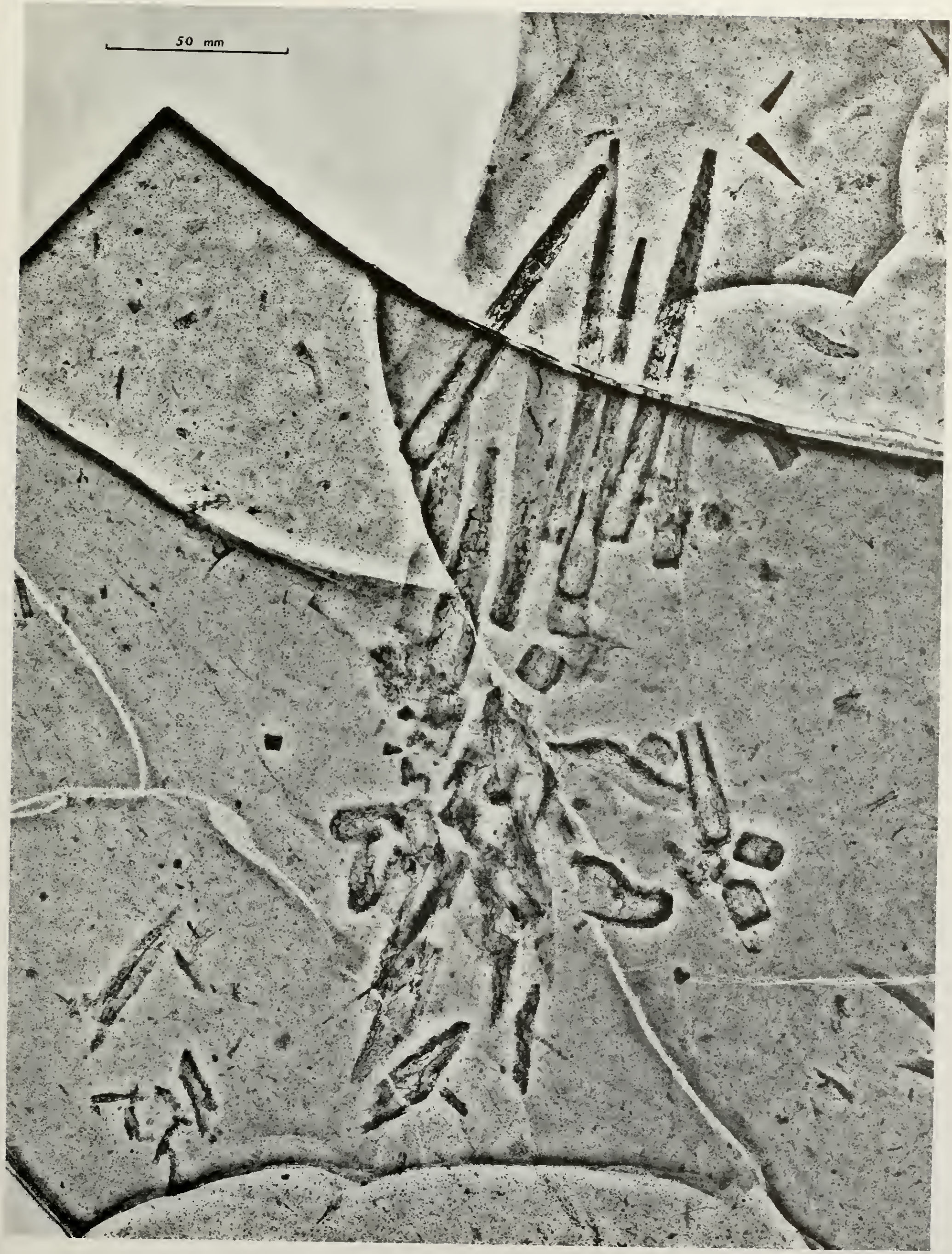
EXPLANATION OF PLATE 38

Radiograph of the chewed remains of a shark tail fin; note broken fin-rays. The specimen consists primarily of the ventral components of the fin. Logan Quarry shale, Logan Quarry, level J, PF 2622.


50 mm

EXPLANATION OF PLATE 39

Radiograph of the chewed remains of a shark tail fin; note the similarity between this specimen and the one illustrated on plate 38. Logan Quarry shale, Logan Quarry, level J, PF 2609.

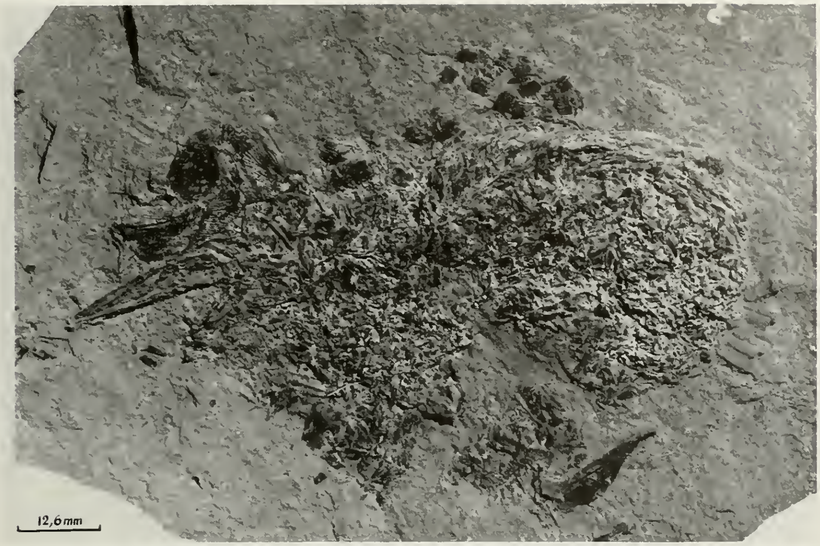

50 mm

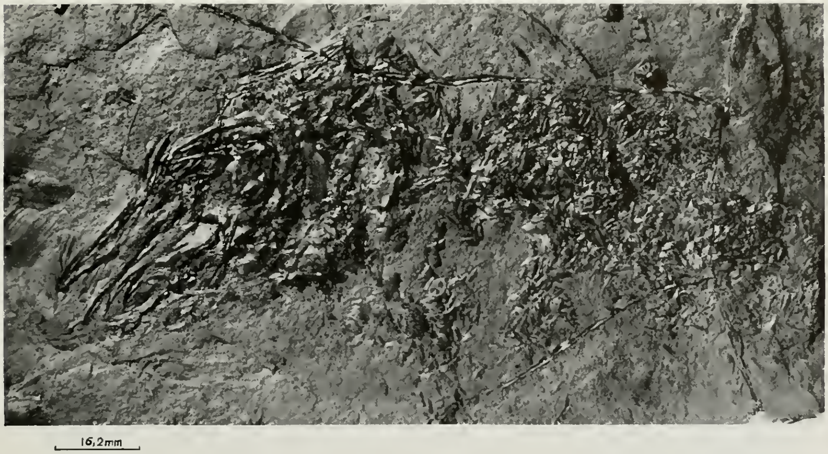
EXPLANATION OF PLATE 40

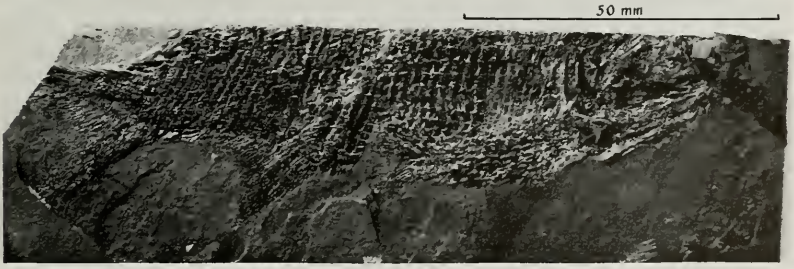
(A) Photograph of a palaeoniscoid specimen that has been regurgitated from a predator's stomach. The packing of the scales is typical of gastric residues (cf. pl. 44), but the skull bones are not completely mixed into the scale mass. Mecca Quarry shale, Mecca Quarry, level A2.3, PF 3022.

(B) Photograph of a palaeoniscoid specimen that may have been severely mouthed or may have been in a predator's stomach for a short period of time. Mecca Quarry shale, Mecca Quarry, level B2.4, PF 3024.

(C) A small palaeoniscoid fish in a near-perfect state of articulation. Logan Quarry shale, Garrard Quarry, Zone 6 (humulite), PF 3190.


12,6mm


16,2mm

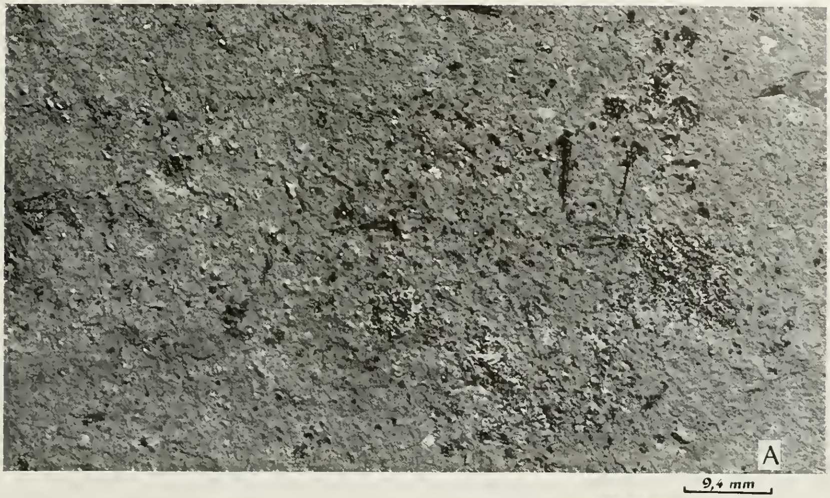

50 mm

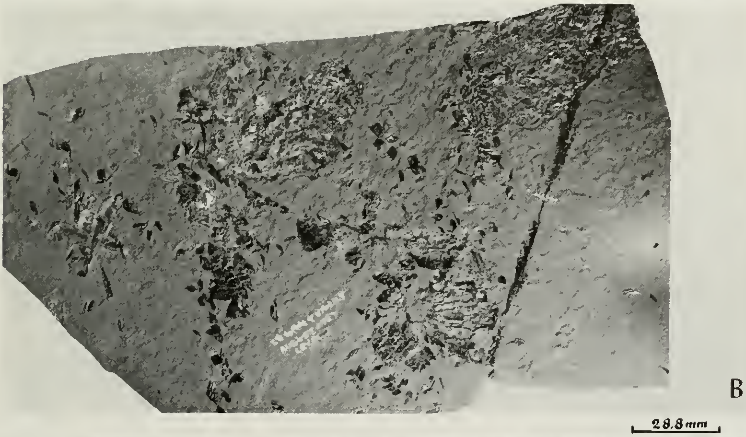
EXPLANATION OF PLATE 41

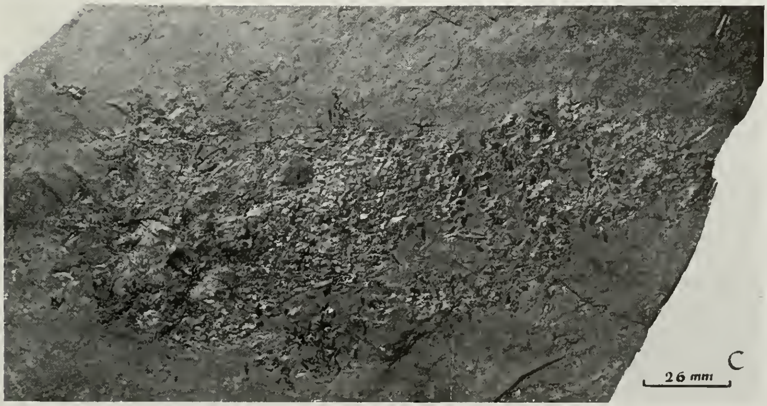
(A) Gastric residue spatter containing acanthodian scales and bones. Mecca Quarry shale, Mecca Quarry, level A3.4, PF 3025.

(B) A palaeoniscoid specimen consisting of pieces of skin (with partially articulated scales) and a scatter of isolated scales. The specimen was probably severely chewed. Logan Quarry shale, Logan Quarry, level J, PF 2604.

(C) A palaeoniscoid fish in slight over-all disarticulation. The principal regions of the body are still discernible. This specimen was probably regurgitated soon after having been ingested. Logan Quarry shale, Logan Quarry, level J, PF 2645.


A
9,4 mm

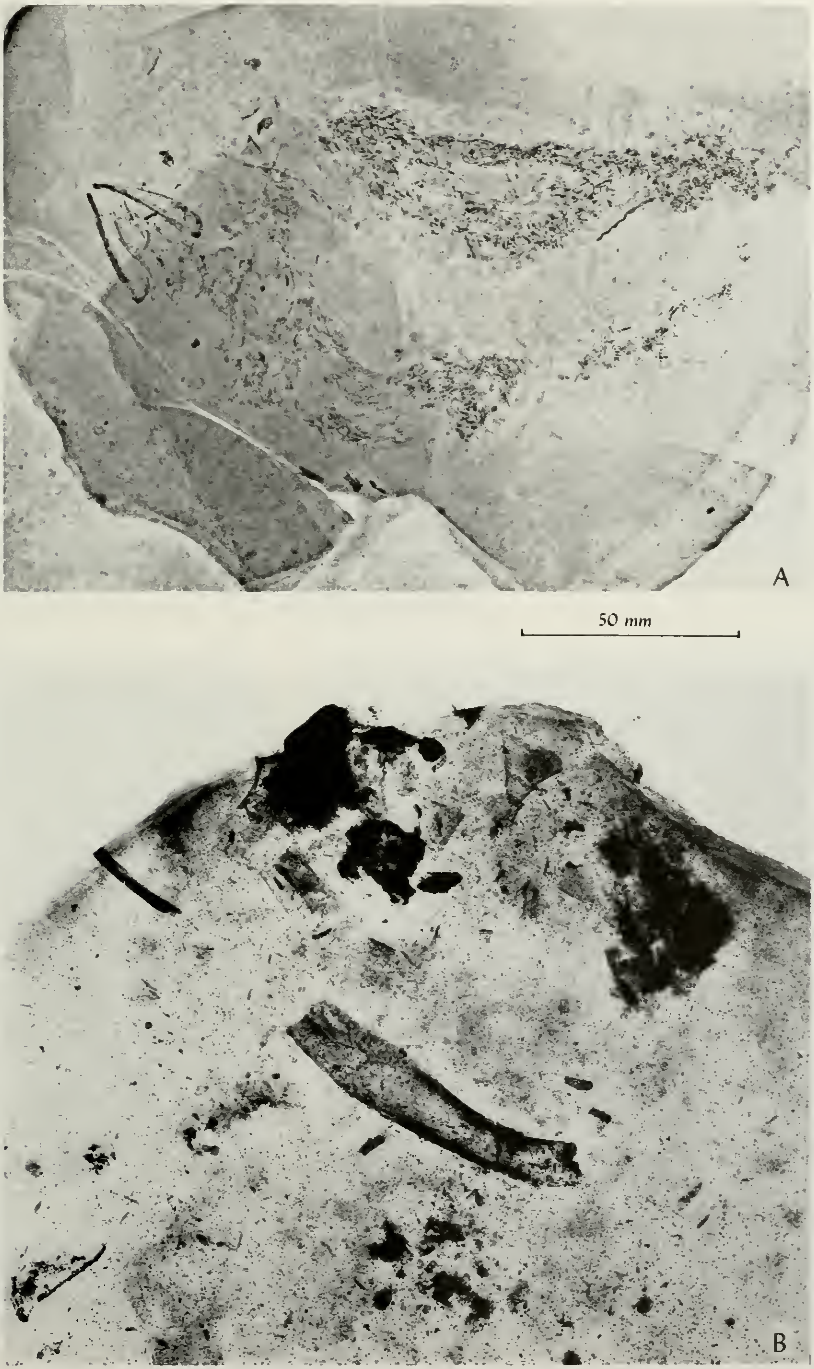

B
28,8 mm


C
26 mm

EXPLANATION OF PLATE 42

(A) Radiograph of palaeoniscoid fish, probably a regurgitated hulk; the scales are not in articulation; the specimen appears to have been partially digested. Logan Quarry shale, Logan Quarry, level K?, PF 2280.

(B) Radiograph of mixed gastric residue. Shark cartilage elements are associated with acanthodian remains. Logan Quarry shale, Logan Quarry, level J, PF 2649.


A
50 mm
B

EXPLANATION OF PLATE 43

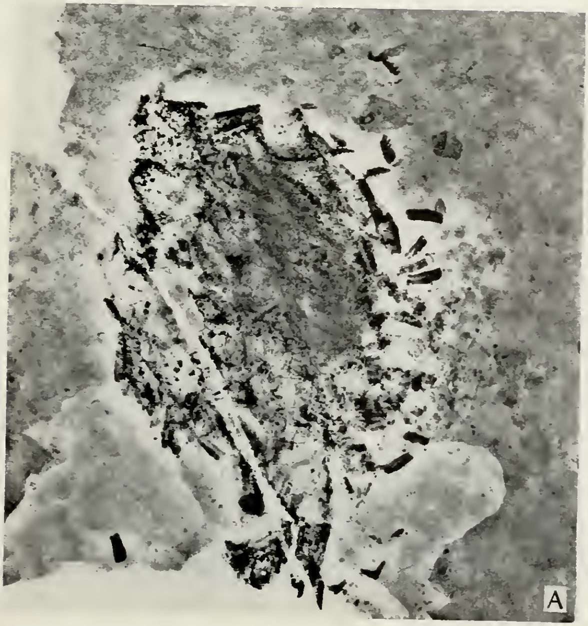
Radiographs of four gastric residue pellets containing shark skulls; note the similarity between these specimens.

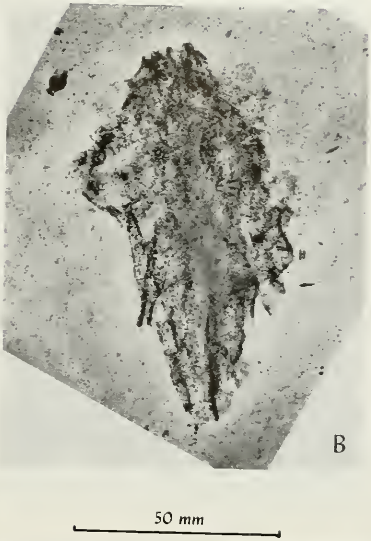
(A) Logan Quarry shale, Logan Quarry, level J, PF 2514.

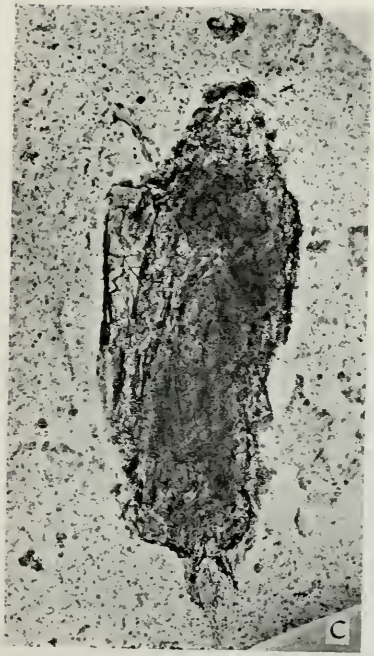
(B) Logan Quarry shale, Logan Quarry, level J, PF 2585.

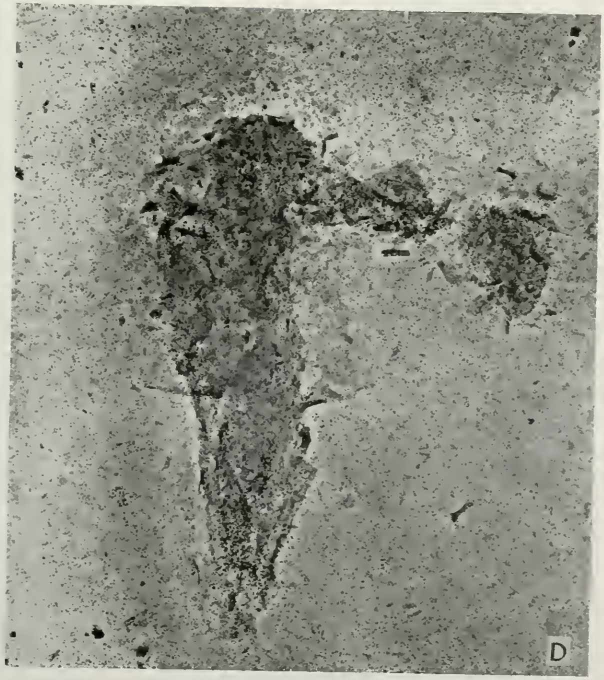
(C) Logan Quarry shale, Logan Quarry, level G, PF 2432.

(D) Logan Quarry shale, Logan Quarry, level J, PF 2502.


A


B
50 mm


C


D

EXPLANATION OF PLATE 44

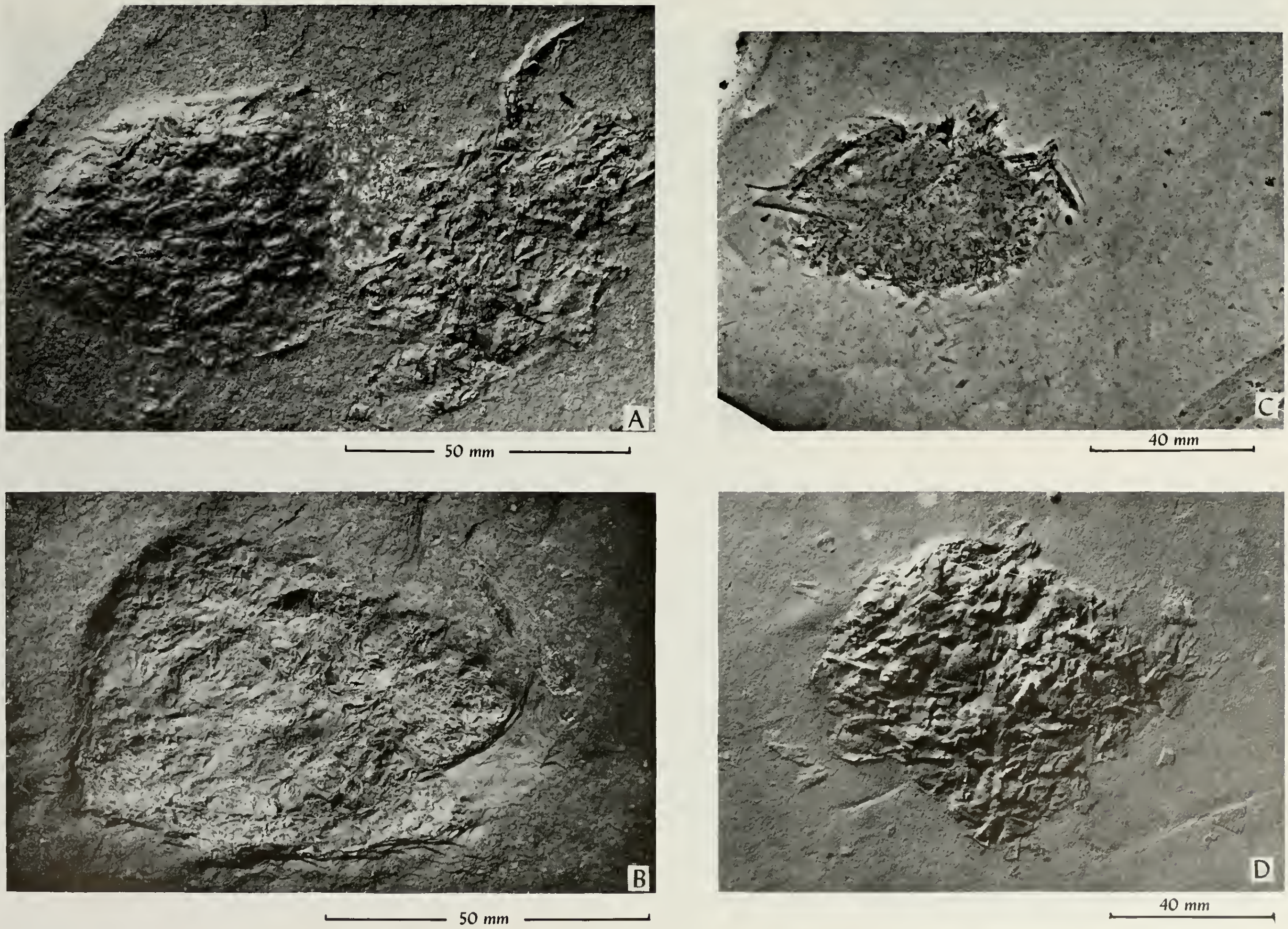
(A) A gastric residue pellet, consisting of packed palaeoniscoid scales and bones. Logan Quarry shale, Logan Quarry, level J, PF 2648.

(B) A gastric residue pellet containing packed palaeoniscoid scales and bones. Logan Quarry shale, Logan Quarry, level J, PF 2647.

(C) Radiograph of a gastric residue pellet containing packed palaeoniscoid scales and bones. Logan Quarry shale, Logan Quarry, level J, PF 2650.

(D) A gastric residue pellet containing minced *Myalina* shells. Logan Quarry shale, Garrard Quarry, Zone 6 (humulite), PF 3189.

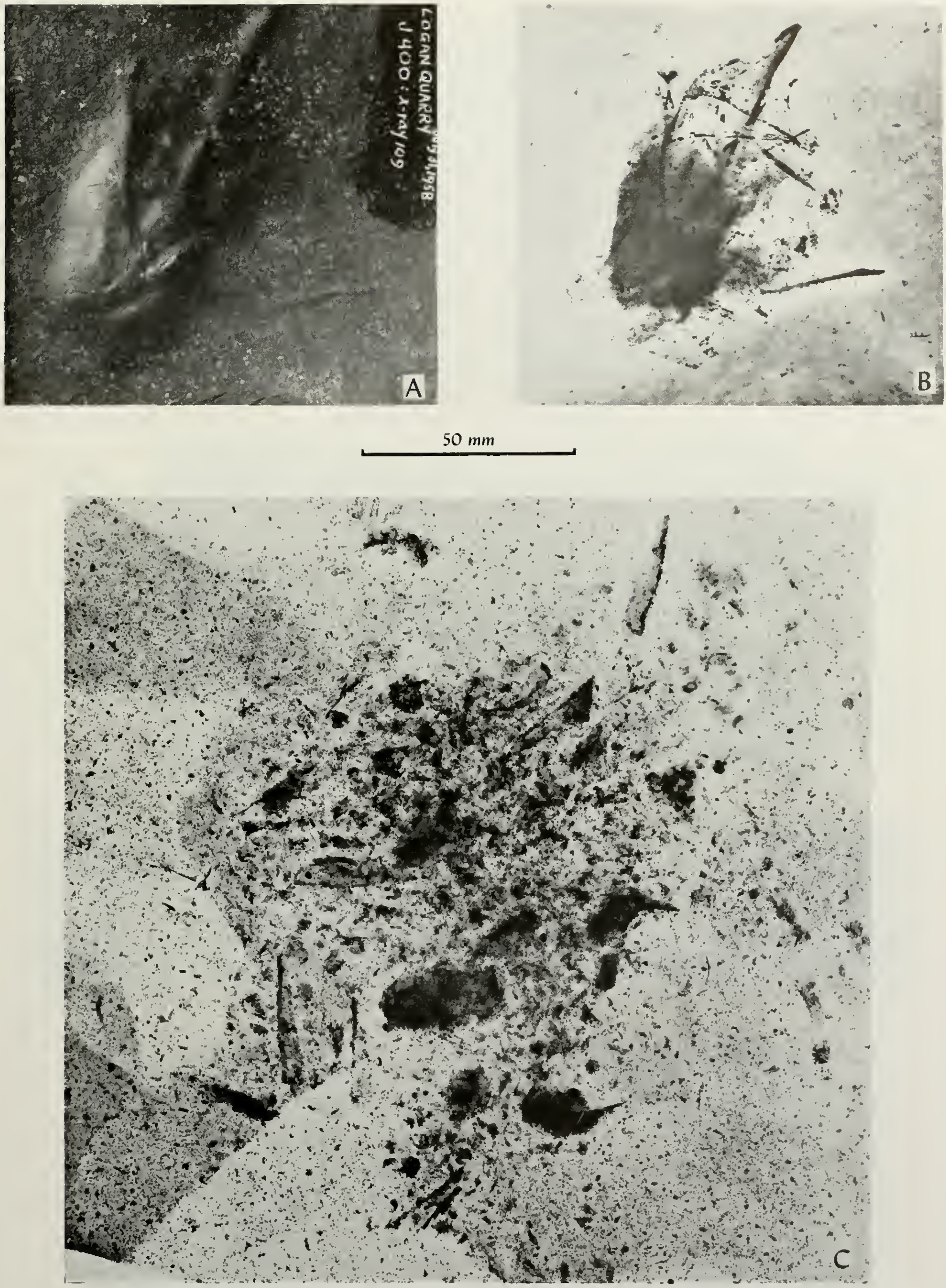
Note the similarity of these pellets, irrespective of the contents.


A
50 mm
C
40 mm
B
50 mm
D
40 mm

EXPLANATION OF PLATE 45

(A and B) Photograph (specimen covered with a film of shale) and radiograph of a gastric residue pellet containing acanthodian scales and spines. Note the arrangement of the spines on one side of the pellet and the thick mass on the opposite side. Logan Quarry shale, Logan Quarry, level J, PF 2643.

(C) Radiograph of a gastric residue spatter containing parts of two palaeoniscoid fishes (four mandibles). Logan Quarry shale, Logan Quarry, level G, PF 2651.


LOGAN QUARRY
J 400 : X-ray 109
A
B
50 mm
C

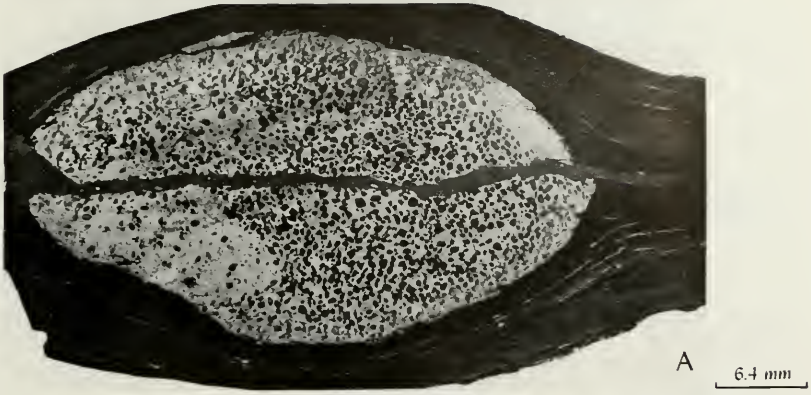
EXPLANATION OF PLATE 46

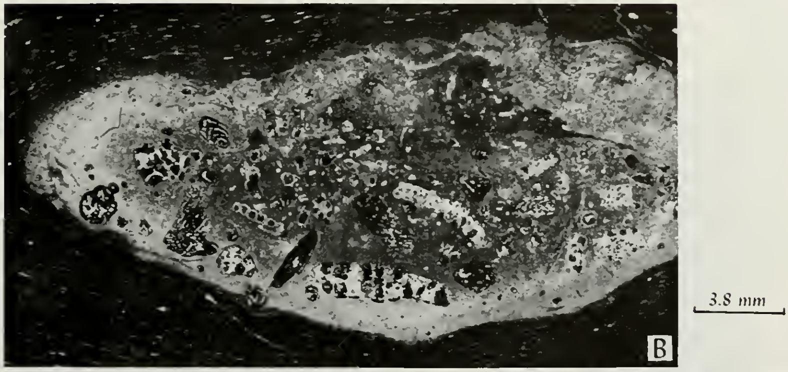
(A) A section across a gastric residue mass (or coprolite) containing quantities of acanthodian scales and gastric or fecal groundmass. The dark horizontal band across the specimen is adhesive used in repair. Logan Quarry shale, Garrard Quarry, Zone 4 (humulite), PF 3187.

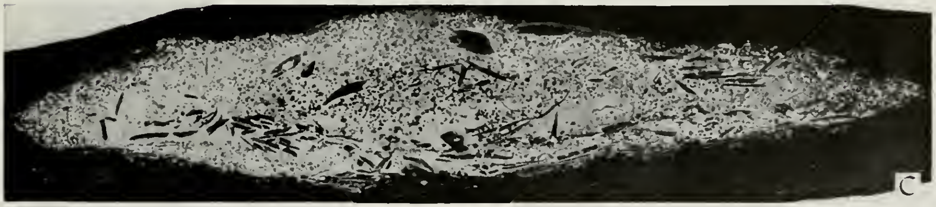
(B) A section of a coprolite containing "placoderm" plates, cartilage fragments, and fecal groundmass. Logan Quarry shale, Logan Quarry, level G, PF 2640.

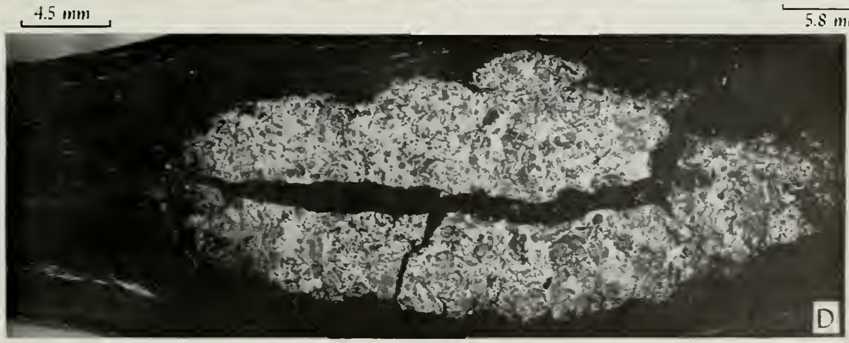
(C) A section of a gastric residue mass containing palaeoniscoid and acanthodian remains and gastric groundmass. Logan Quarry shale, Logan Quarry, level J, PF 2634.

(D) A section through a coprolite that does not contain recognizable skeletal remains. The fecal groundmass is highly pyritic and vacuities within it have been secondarily filled with calcite. The irregular black band across the specimen is adhesive used in repair. Logan Quarry shale, Logan Quarry, level G, PF 2642.


A
6.4 mm


3.8 mm
B


C
5.8 mm


4.5 mm
D

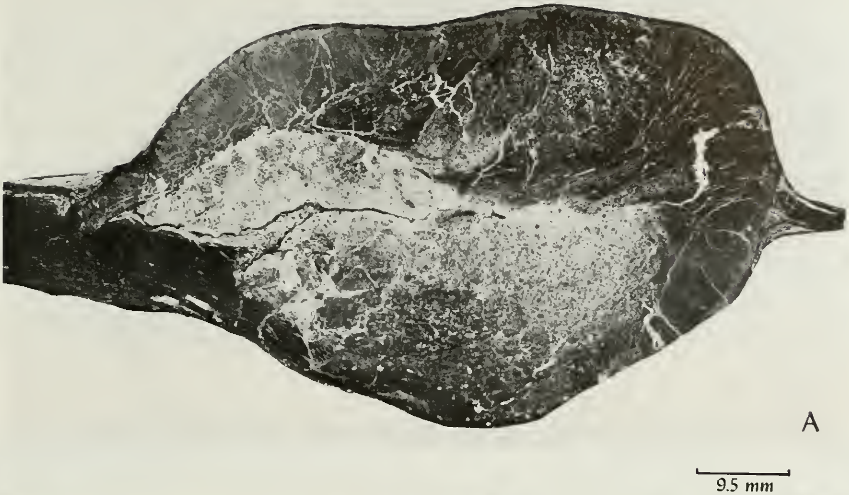
EXPLANATION OF PLATE 47

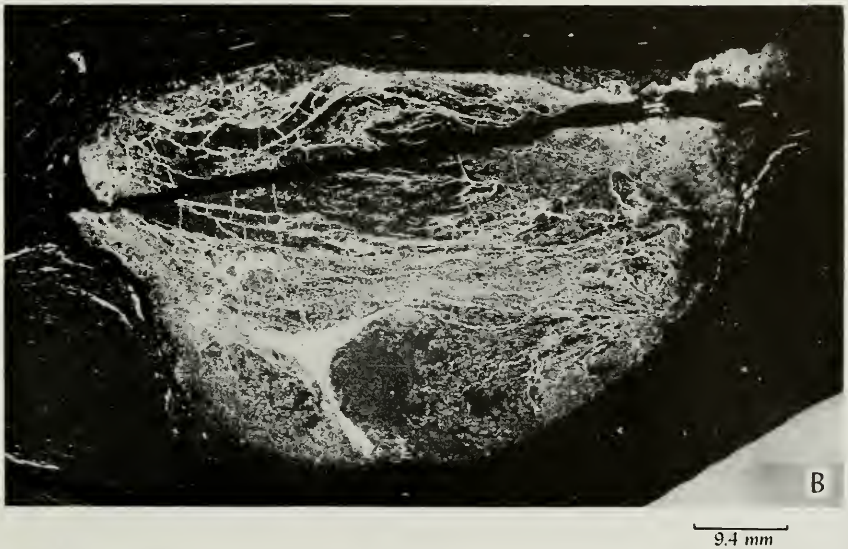
(A) A section through a large massive coprolite, showing a number of fecal boli that may be distinguished by color, texture, and density. Note the differences in the shrinkage pattern of the different fecal components. The projections at the ends of the specimen are bits of adhering shale. Logan Quarry shale, Logan Quarry, level G, PF 2641.

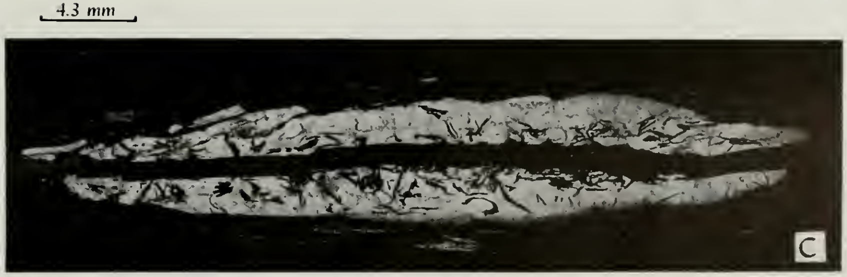
(B) A section through a coprolite that shows very marked flattening in its upper portion due to aerobic decay in that area. The fecal boli were apparently of different consistency as they arrived in the rectum of the bearer; hence the kneaded appearance of some of the components. The shrinkage pattern may also be related to the different fecal consistency. Logan Quarry shale, Logan Quarry, level G, PF 2639.

(C) A section through a spiral coprolite containing palaeoniscoid scales and fecal groundmass. Logan Quarry shale, Garrard Quarry, Zone 4 (humulite), PF 3188.

The horizontal black bands across the specimens illustrated in B and C are streaks of adhesive.


A
9.5 mm


B
9.4 mm

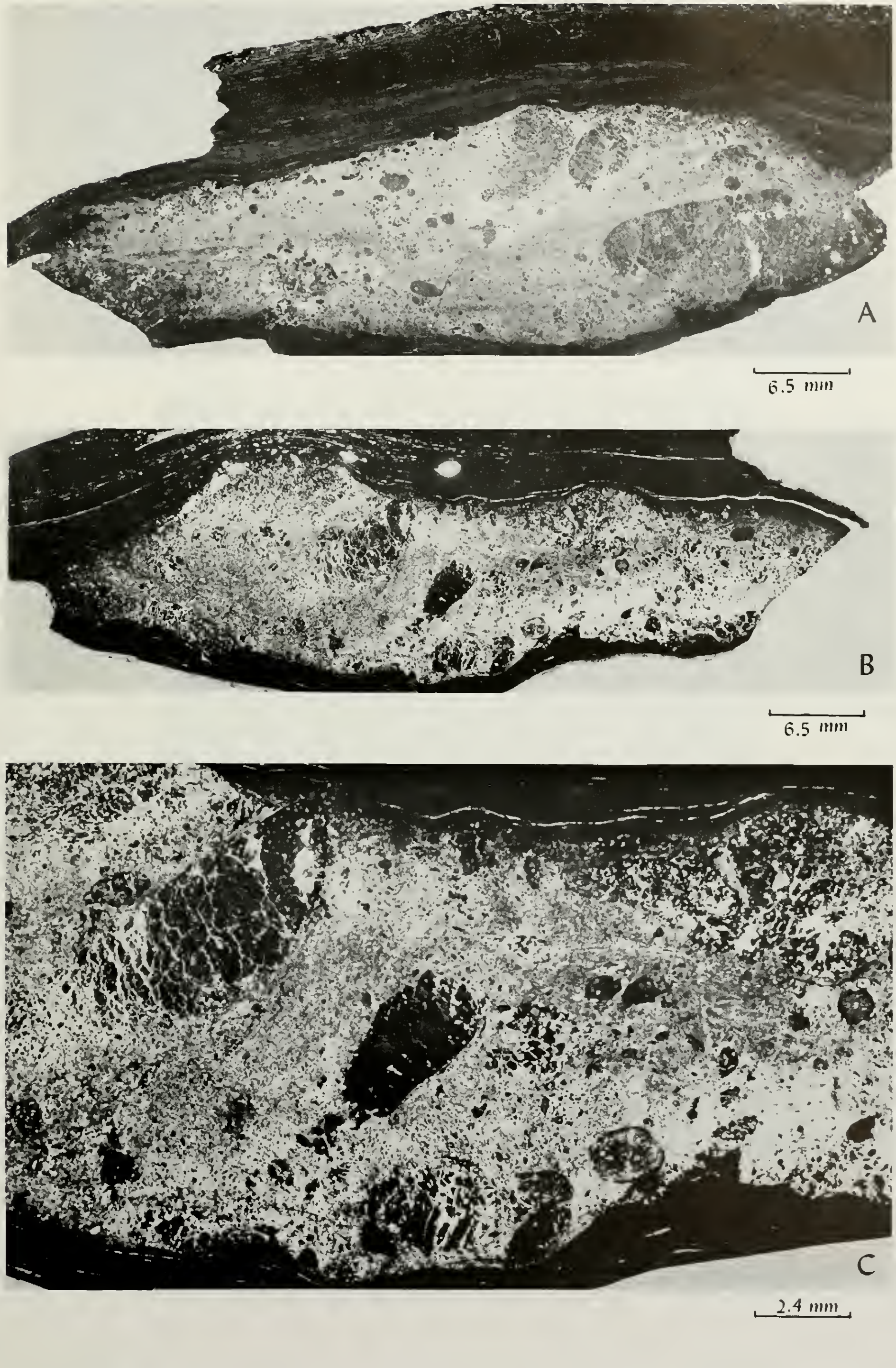

4.3 mm
C

EXPLANATION OF PLATE 48

(A) A section through a coprolite consisting of an overall groundmass in which smaller boli have been embedded. Logan Quarry shale, Logan Quarry, level J, PF 2646.

(B) A thin section of the same specimen, showing the different appearance and shrinkage pattern of the inclusions.

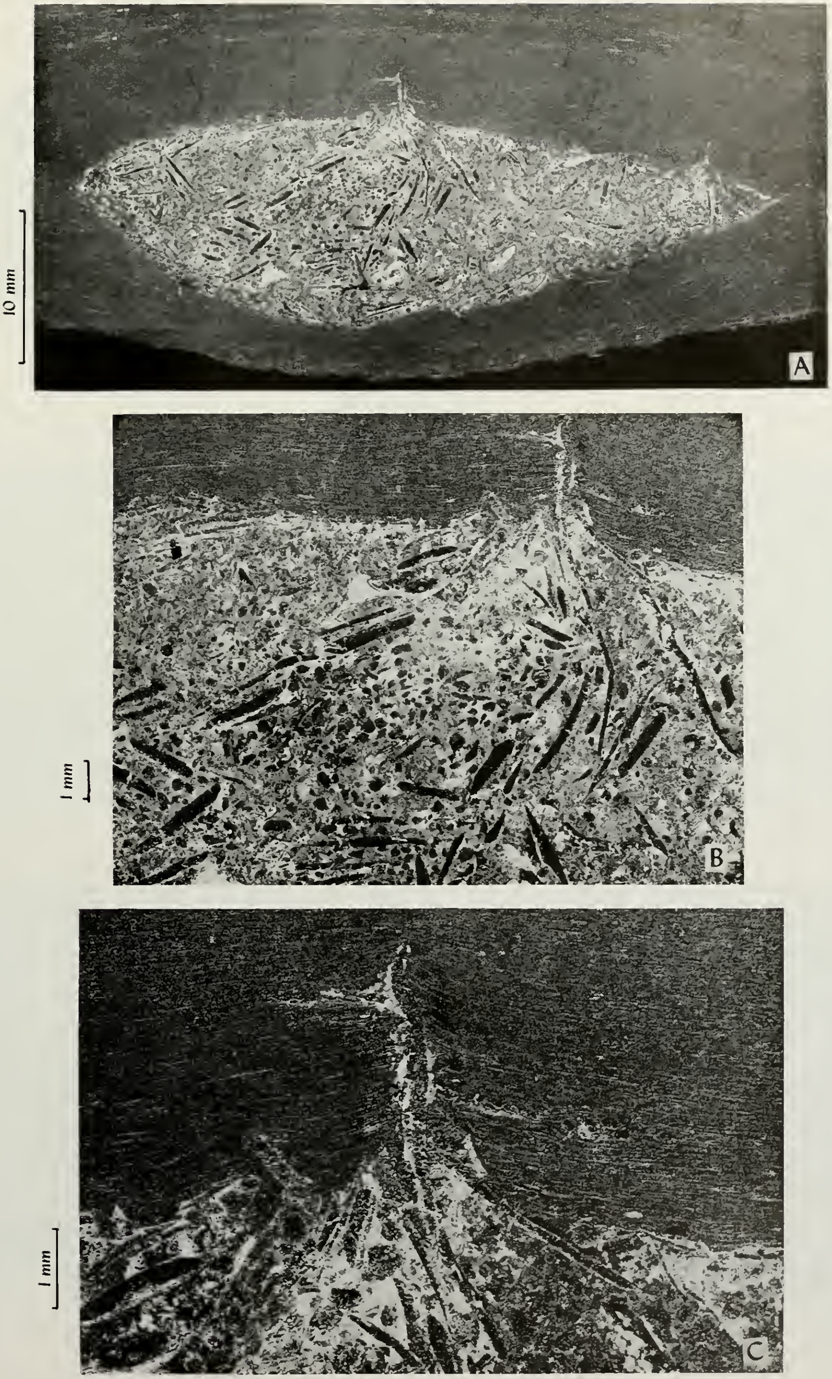
(C) Detail of the same thin section, showing the effects of intestinal kneading on the fecal bolus (upper left corner of picture). The upper outline is very sharp, but the lower end has been worked into the surrounding fecal mass. The shrinkage cracks appear to be related to this movement.


A
6.5 mm
B
6.5 mm
C
2.4 mm

EXPLANATION OF PLATE 49

(A) A section through a gastric residue pellet containing palaeoniscoid scales (black bars), acanthodian scales (black squares), and gastric groundmass. Two of the palaeoniscoid scales protrude beyond the mass along its upper border and a small amount of gastric groundmass extends from the tip of the protruding scale in the middle of the pellet along a microbedding plane to the left (for interpretation of this phenomenon see fig. 37). Logan Quarry shale, Logan Quarry, level J, PF 2219.

(B and C) Detail views of the central area of the same pellet. Note the arrangement of the palaeoniscoid scales, and, (C), the details of the microbedding of the shale against the protruding scale. The shale is 2 mm. thick between the surface of the pellet and the "flag" of groundmass to the left of the protruding scale.

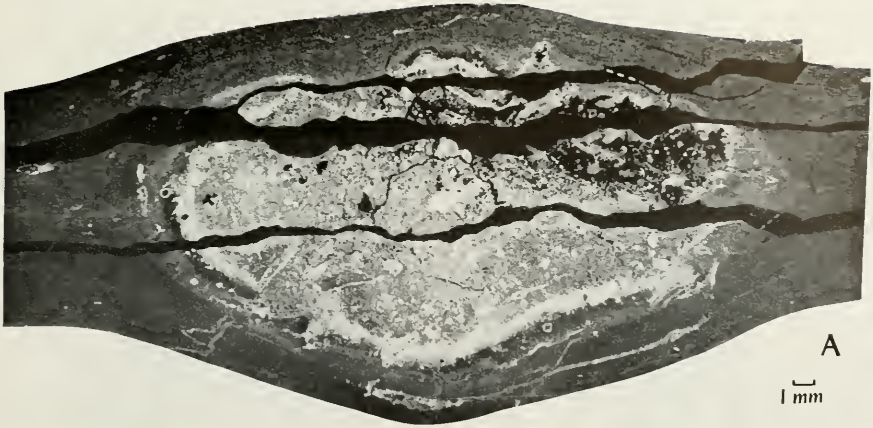

10 mm
A
1 mm
B
1 mm
C

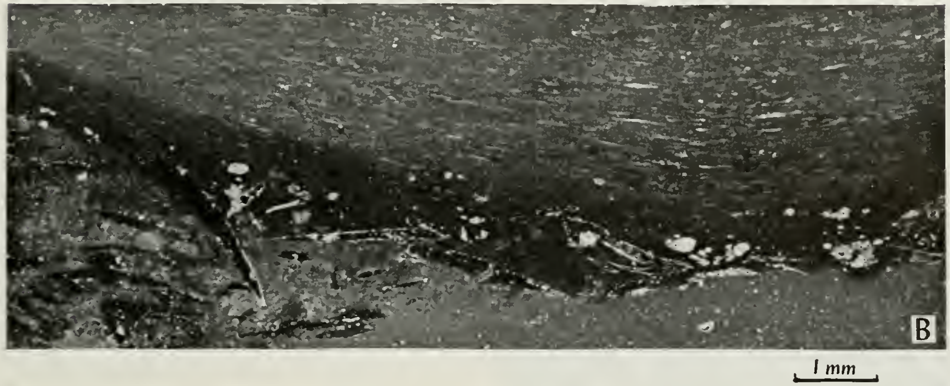
EXPLANATION OF PLATE 50

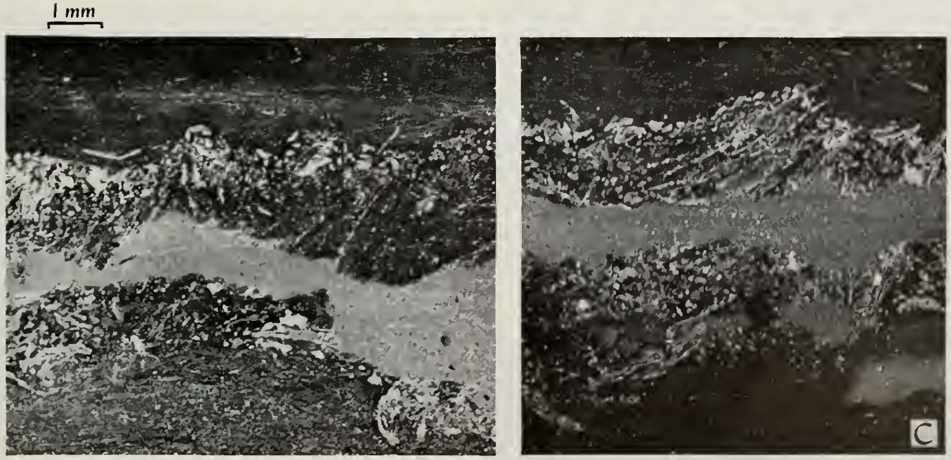
(A) A section through coprolite containing fecal groundmass and a few palaeoniscoid scales. There is a marked peripheral concentration of the sulfides, but the fecal mass extends beyond the heaviest sulfide concentration, as indicated by the white broken lines. Surrounding the fecal mass there is a zone (not clearly visible on the photograph) consisting of dense waxy shale mixed with decomposed fecal matter. This is also present beneath the coprolite, suggesting more intensive aerobic activity than in most specimens. The irregular horizontal black streaks are adhesive used in repairing the specimen. Mecca Quarry shale, Mecca Quarry, level B2.4, PF 2703.

(B) A section through a thin gastric residue mass containing palaeoniscoid scales. The aerobic decay produced gas bubbles that were vented to the surface and resulted in the mixture of decay products with the mud that had meantime accumulated over the mass. The layer so formed is fine-textured and blacker than the shale above it and may thus be easily distinguished. In specimens from the Mecca Quarry this layer measures about 1 mm. The gray substance beneath the scales is epoxy resin. Mecca Quarry shale, Mecca Quarry, level A1.4, PF 2704.

(C) A section through another thin gastric residue mass containing palaeoniscoid scales. Gas bubbles vented during the aerobic phase of degradation produced a very irregular surface on the gastric mass, with scales protruding at various angles. The black waxy layer is present as in B, but it is not quite as sharply marked. Epoxy resin forms a broad light-gray band through the specimen. Mecca Quarry shale, Mecca Quarry, level B2.3, PF 3018.


A
1 mm


B
1 mm

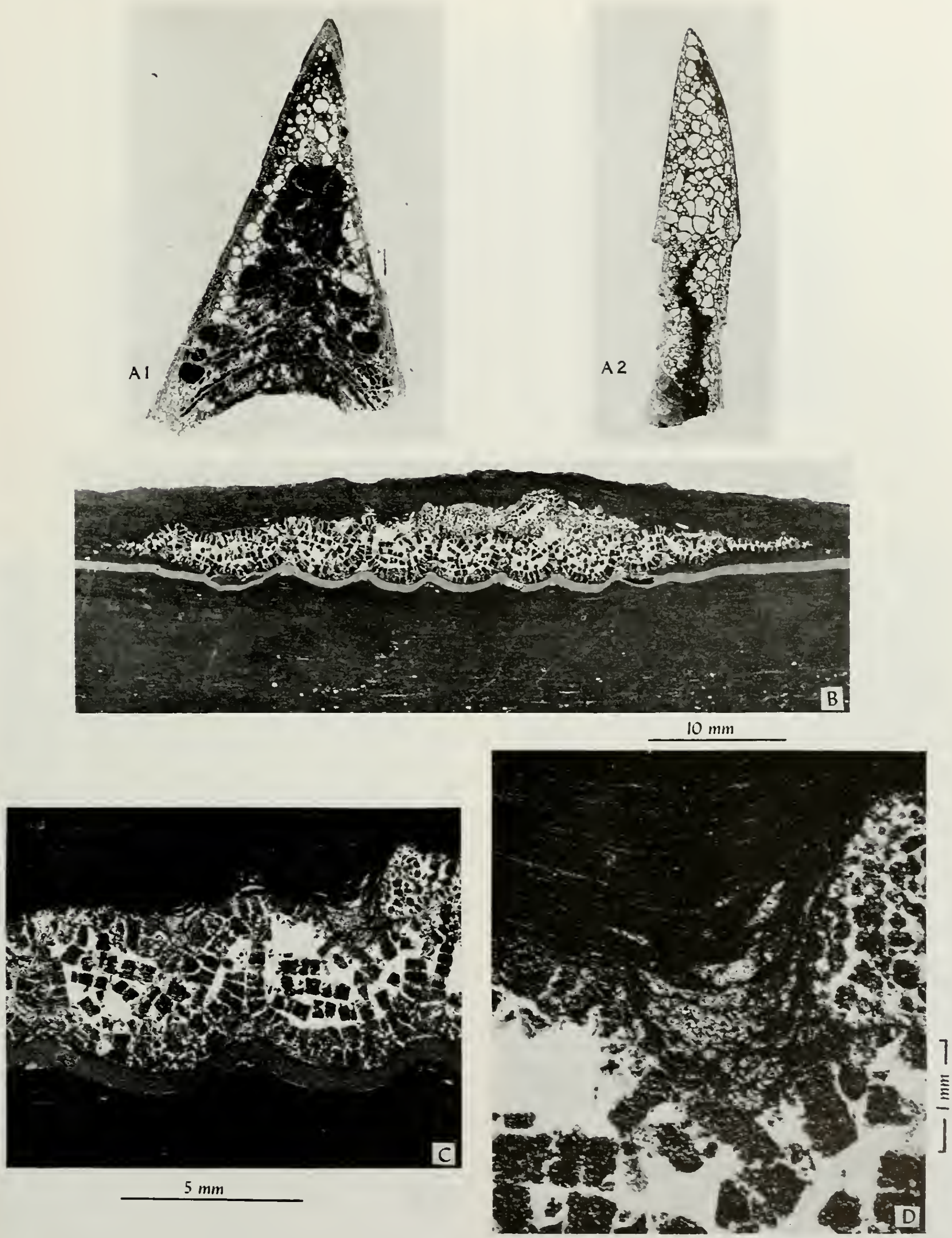

1 mm
C

EXPLANATION OF PLATE 51

(A) Cross sections through two peripheral plates of marine turtles from the Mooreville chalk of the Cretaceous Selma formation of Alabama (from Zangerl, 1948, pl. 1; about × 2). In one plate, A1, the interior bone cavities had been filled with bitumen (black areas) or calcite (white areas) prior to compaction of the sediment; hence no crushing took place. In the other, A2, the cavities of the spongy bone had been filled with calcite only in the distal area of the plate; in the proximal half the cavities remained hollow and the spongework collapsed under compaction (broken bone trabeculae form a dark band). Spongy bone cavities as preserved in the Mecca and Logan Quarry shales are most often empty and not collapsed (see pl. 53, C).

(B) Cross section through a shark fin from Logan Quarry shale, Logan Quarry, level J, PF 2212, showing a number of significant depositional features. The light even band below the specimen is epoxy resin with which plate and counterplate had been rejoined. Our interpretation of the sequence of events that produced them is illustrated in figure 40. Note the undisturbed arrangement of the calcified cartilage prisms of the fin-rays along the under side of the fossil. Along the upper side, the prism rings are broken and the pieces have settled into the interior of the fin-rays. The spaces between them are filled with calcite, not shale.

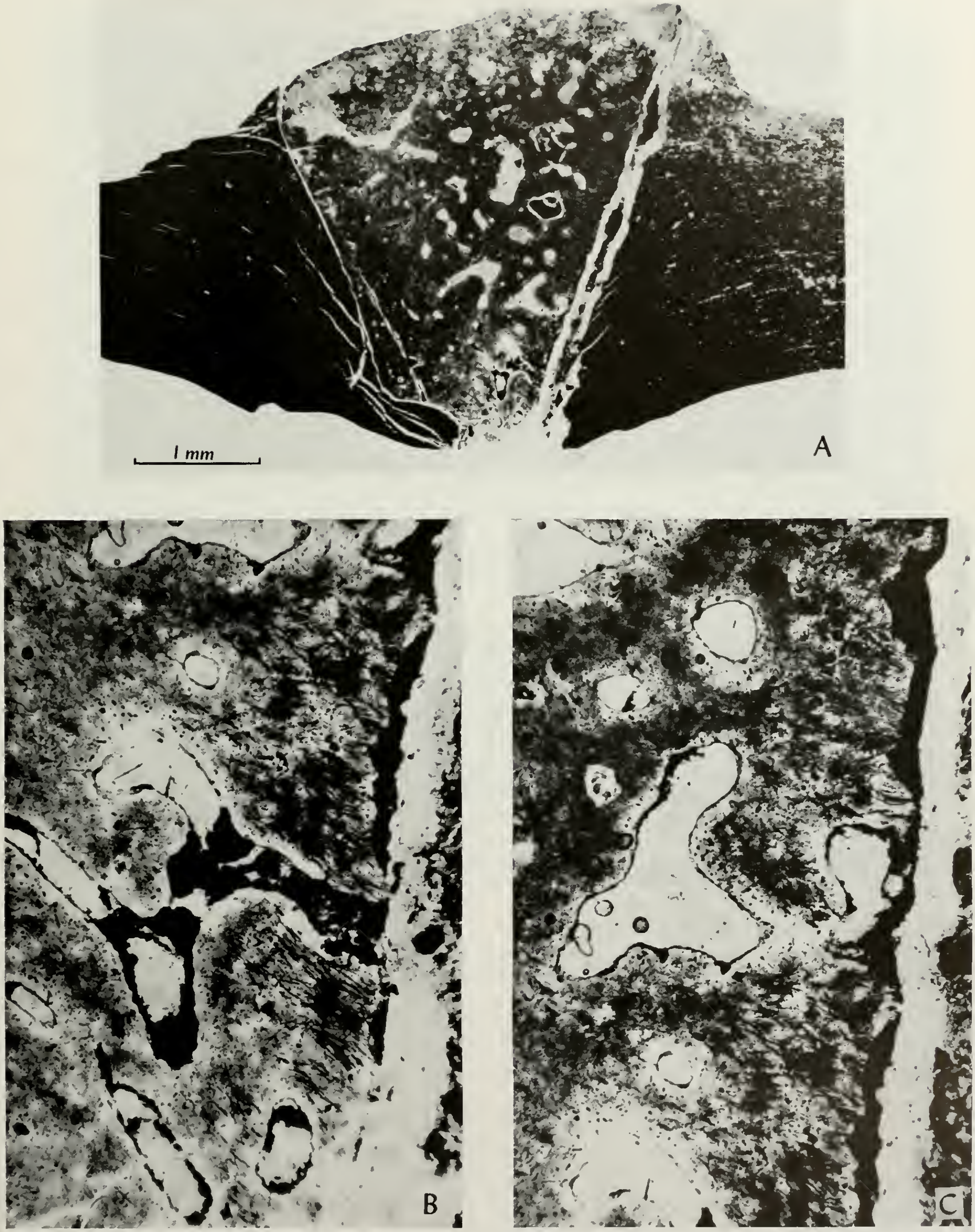
(C and D) Enlarged details of the same specimen. Note the sphalerite crystals interbedded with the sediment above the broken fin-rays and below between adjacent fin-rays. The cartilage prisms are now black in color.

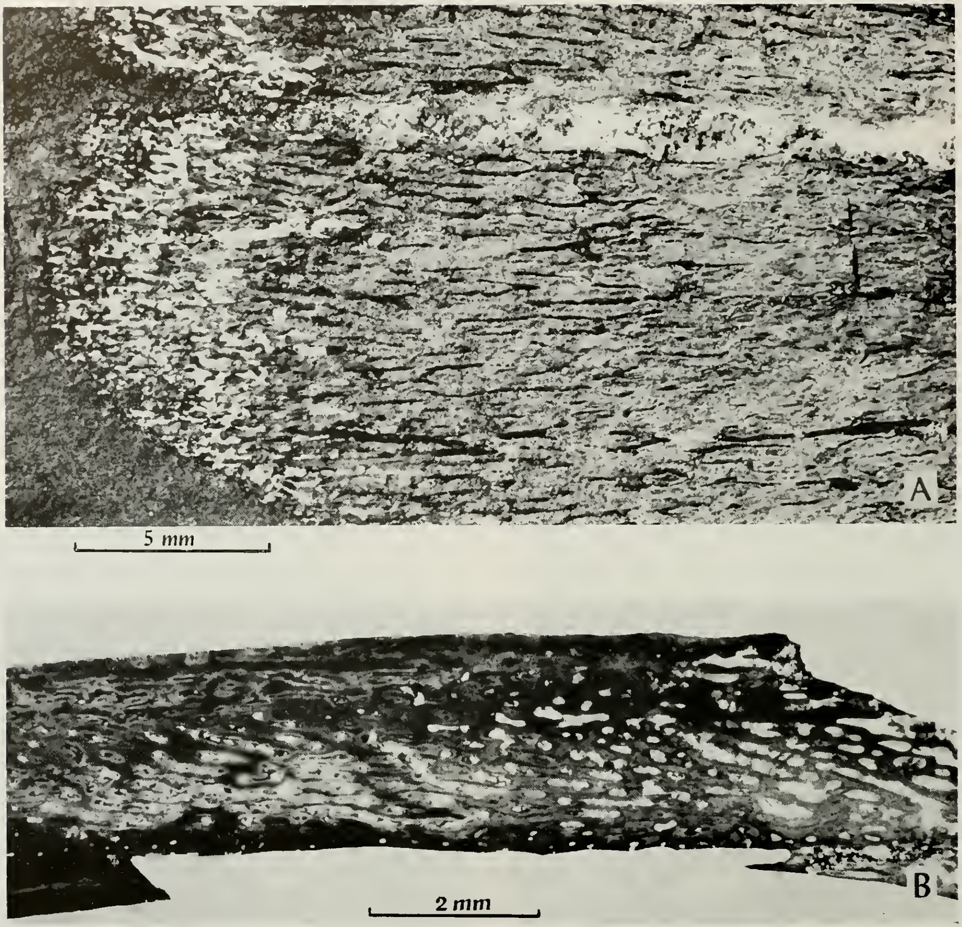

A1
A2
B
10 mm
C
5 mm
D
1 mm

EXPLANATION OF PLATE 52

(A) A thin section through a piece of shale containing a *Petrodus* placoid scale. The base of the scale—the surface with which it was attached to the skin—faces to the right in the picture. Note the air-filled spaces within the dentine substance. These spaces are connected with a number of pores along the base of the scale. Mecca Quarry shale, Mecca Quarry, level B1.4, PF 3023.

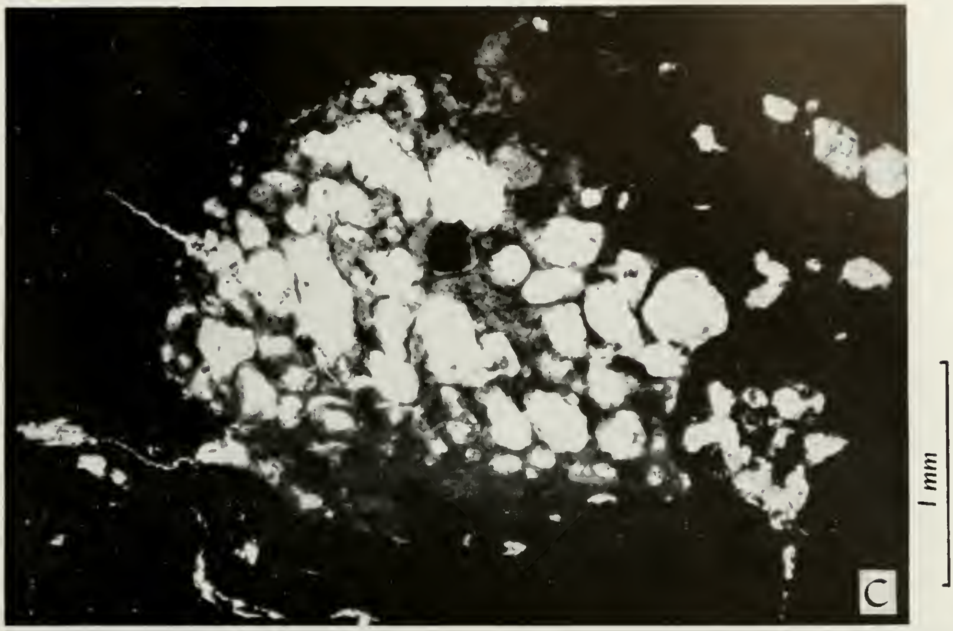
(B and C) Details of the same specimen; two pores along the base of the scale have been blocked by opaque plant degradation debris. This shows that the opaque material was particulate matter at the time of deposition (rather than colloidal) and that compaction was not severe enough to squeeze the sediment into the cavity system, which remained vacant. The presence of colloidal substances is evidenced by the dark brown outlines of the cavities and the brown fillings in the tiny dentinal tubules (black in photograph).


1 mm
A
B
C



(A) The longitudinally broken posterior end of an edestid "tooth spine," showing most of the internal canal system filled with air; at the left margin secondary infilling with gypsum has taken place. Mecca Quarry shale, Mecca Quarry, level B1.3, PF 3027.

(B) A longitudinal thin section through an acanthodian pectoral spine, showing most of the internal canal system empty and uncrushed. Mecca Quarry shale, Mecca Quarry, level A3.3, slide no. 195.



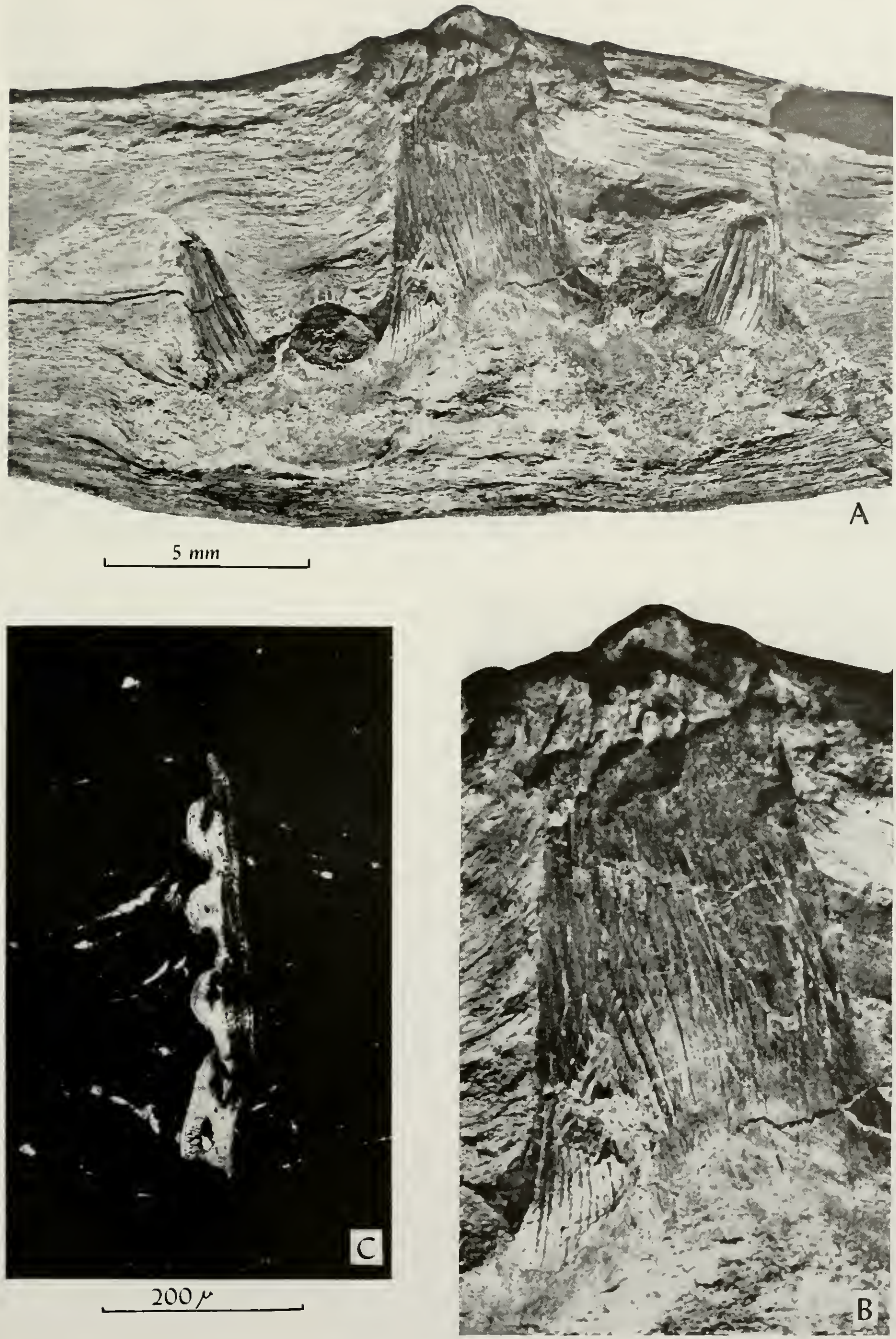
(C) A thin section through the posterior end of a palaeoniscoid mandible. The interior of the bone is a very delicate spongework of bony trabeculae. The cavities are air-filled and not collapsed. (See also pl. 51, A.) Mecca Quarry shale, Mecca Quarry, level A3.3, slide no. 196.

EXPLANATION OF PLATE 54

(A) A cladodontid tooth embedded vertical to bedding. Mecca Quarry shale, Mecca Quarry, level B4.2/3, PF 3026.

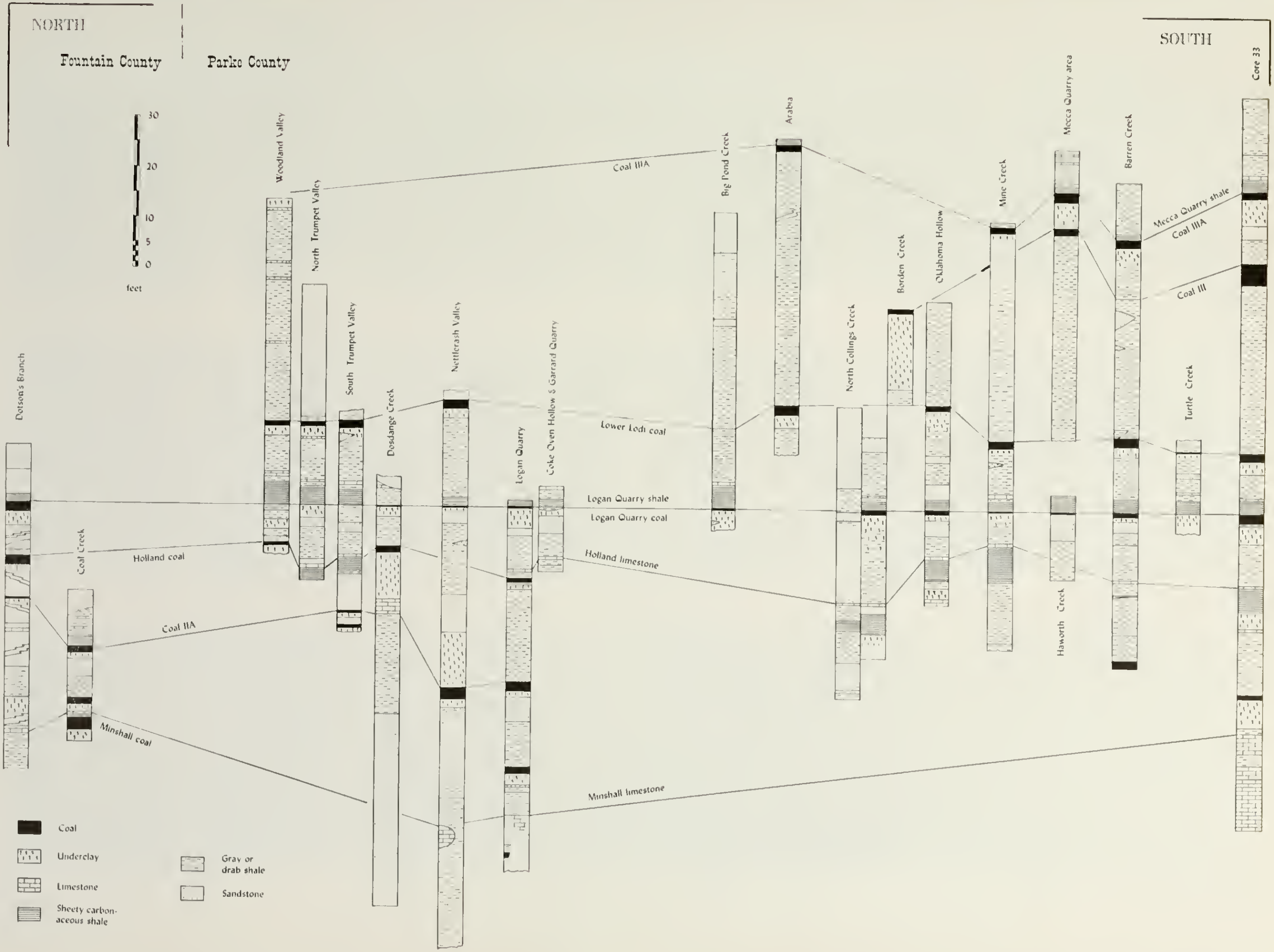
(B) A detail of the same specimen, showing very fine crack lines (white) traversing the tooth ornament.

(C) A minute fish scale embedded vertical to bedding. Logan Quarry shale, Logan Quarry, level M, slide no. 57. The tiny scale, with its weak points between the tubercles (or ridges), shows no signs of breakage or compression.


A
5 mm
C
200 μ
B

EXPLANATION OF PLATE 55

A correlation chart of stratigraphic sections from Core 33 to Dotson's Branch and from the Minshall limestone to the Velpen limestone. Column between North Collings Creek and Borden Creek is South Collings Creek.


NORTH
Fountain County
Parke County
SOUTH
30
20
10
5
0
feet
Dotson's Branch
Coal Creek
Woodland Valley
North Trumpet Valley
South Trumpet Valley
Dosdange Creek
Nettlerash Valley
Logan Quarry
Coke Oven Hollow & Garrard Quarry
Big Pond Creek
Arabia
North Collings Creek
Borden Creek
Oklahoma Hollow
Mine Creek
Mecca Quarry area
Haworth Creek
Barren Creek
Turtle Creek
Core 33
Coal IIIA
Lower Lodi coal
Logan Quarry shale
Logan Quarry coal
Holland coal
Holland limestone
Coal IIA
Minshall coal
Minshall limestone
Mecca Quarry shale
Coal IIIA
Coal III
Coal
Underclay
Limestone
Sheety carbonaceous shale
Gray or drab shale
Sandstone

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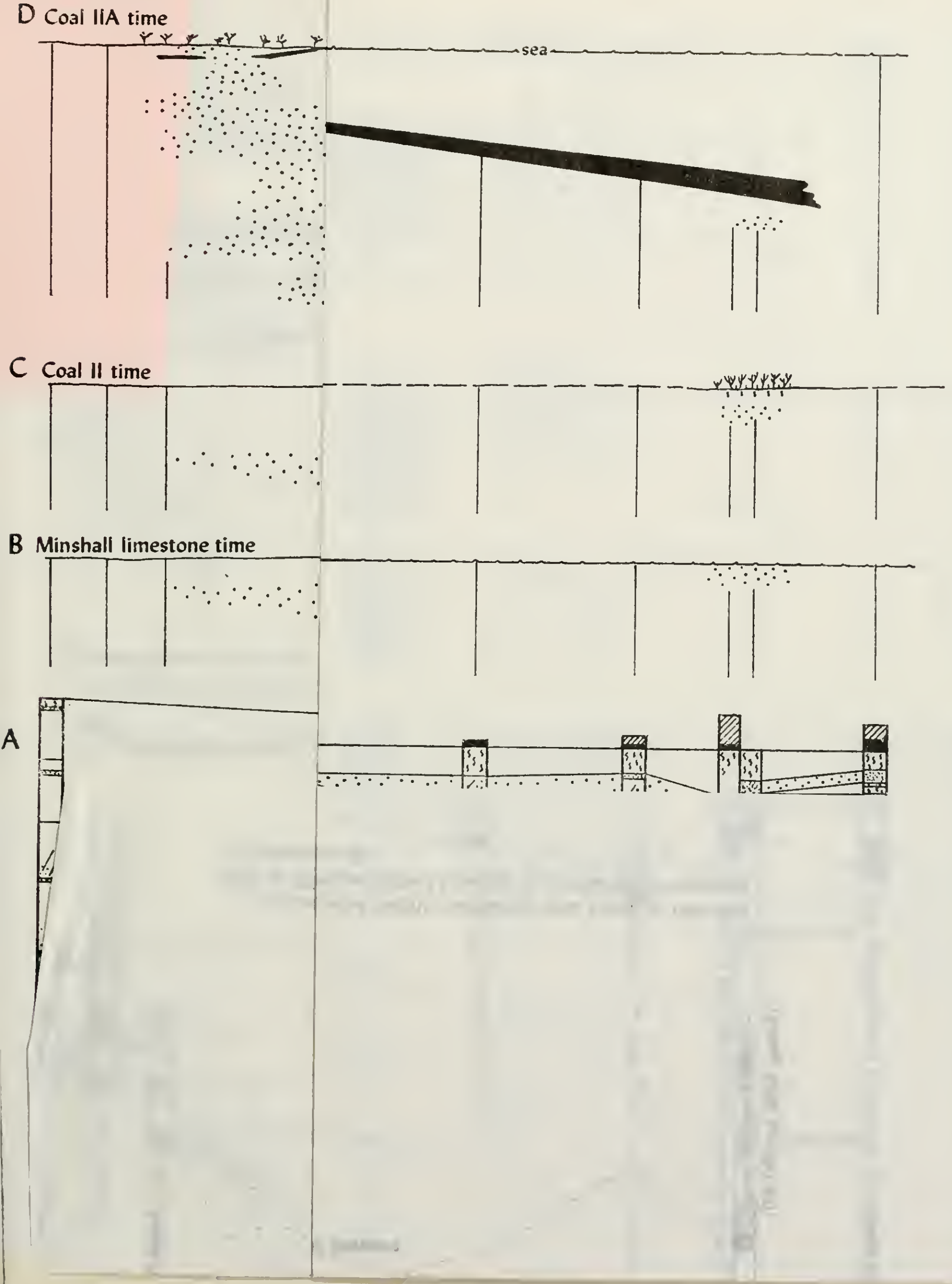
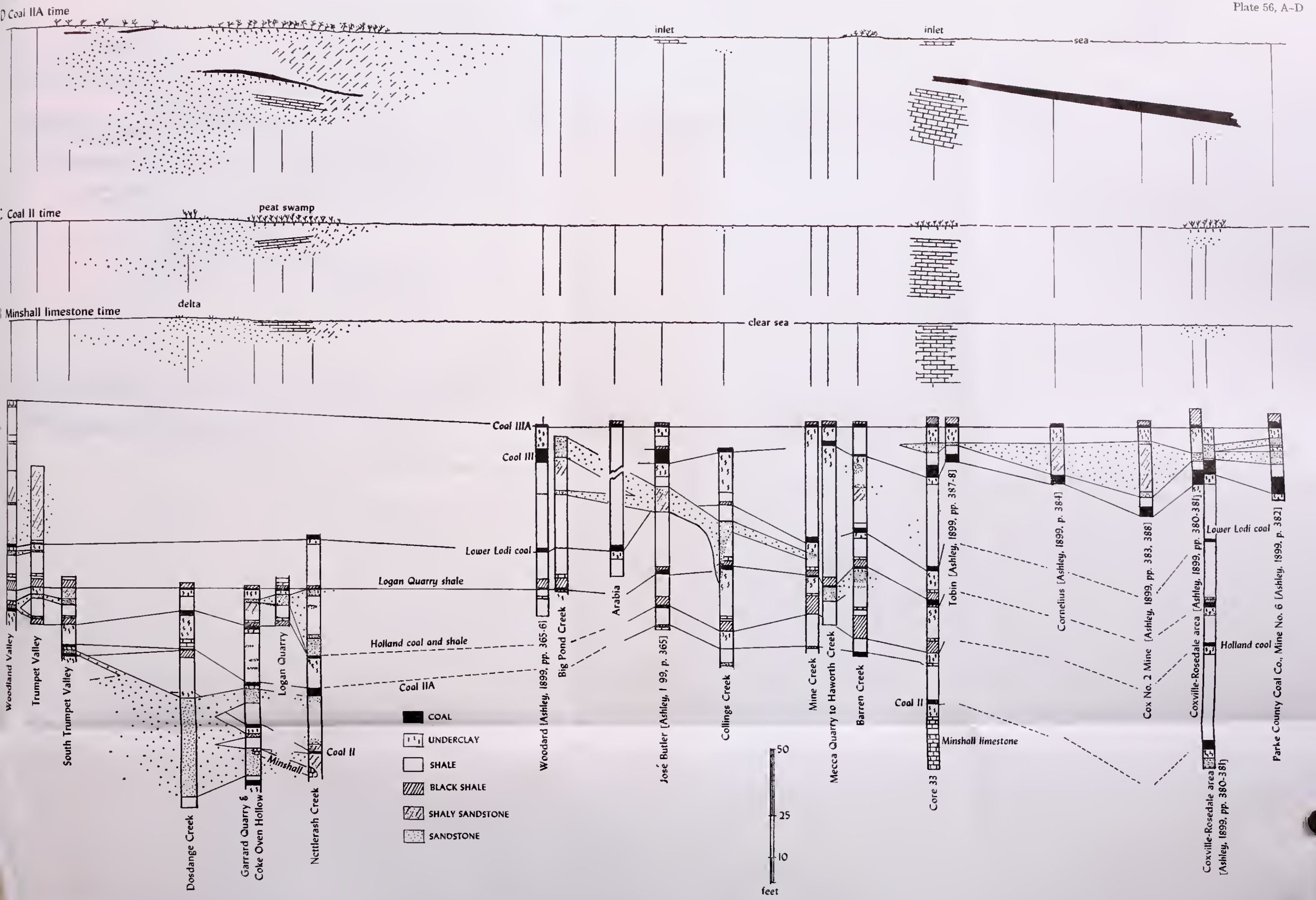
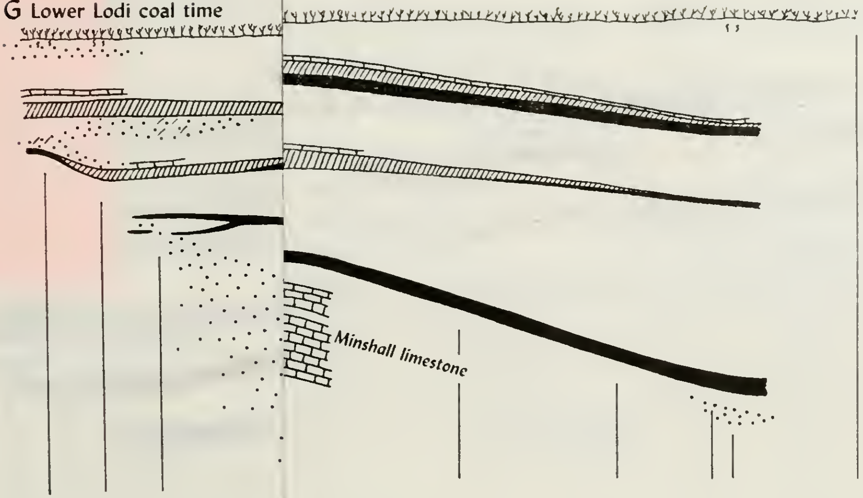

D Coal IIA time
sea
C Coal II time
B Minshall limestone time
A


D Coal IIA time
inlet
inlet
sea
Coal II time
peat swamp
Minshall limestone time
delta
clear sea
Coal IIIA
Cool III
Lower Lodi coal
Logan Quarry shale
Holland coal and shale
Coal IIA
Coal II
Minshall
Coal II
Minshall limestone
Lower Lodi coal
Holland cool
COAL
UNDERCLAY
SHALE
BLACK SHALE
SHALY SANDSTONE
SANDSTONE
50
25
10
feet
Woodland Valley
Trumpet Valley
South Trumpet Valley
Dosdange Creek
Garrard Quarry & Coke Oven Hollow
Logan Quarry
Nettlerash Creek
Woodard [Ashley, 1899, pp. 365-6]
Big Pond Creek
Arabia
José Butler [Ashley, 1 99, p. 365]
Collings Creek
Mine Creek
Mecca Quarry to Haworth Creek
Barren Creek
Core 33
Tobin [Ashley, 1899, pp. 387-8]
Cornelius [Ashley, 1899, p. 384]
Cox No. 2 Mine [Ashley, 1899, pp. 383, 388]
Coxville-Rosedale area [Ashley, 1899, pp. 380-381]
Coxville-Rosedale area [Ashley, 1899, pp. 380-381]
Parke County Coal Co., Mine No. 6 [Ashley, 1899, p. 382]

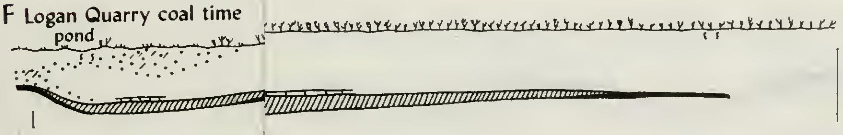
EXPLANATION OF PLATE 56

Successive depositional stages from Minshall limestone time to Coal IIIA time on a line from Coxville to Woodland Valley. (A) Correlation diagram of the beds in this interval. (B–I) Interpretation of topography and environment during nine stages in the development of the region. It is suggested that subsidence of the coastal plain proceeded unevenly, the most rapidly subsiding area being in different places at different times. It is probable that the major streams shifted laterally but remained in the same vicinity throughout the time represented. Compare Figure 46.

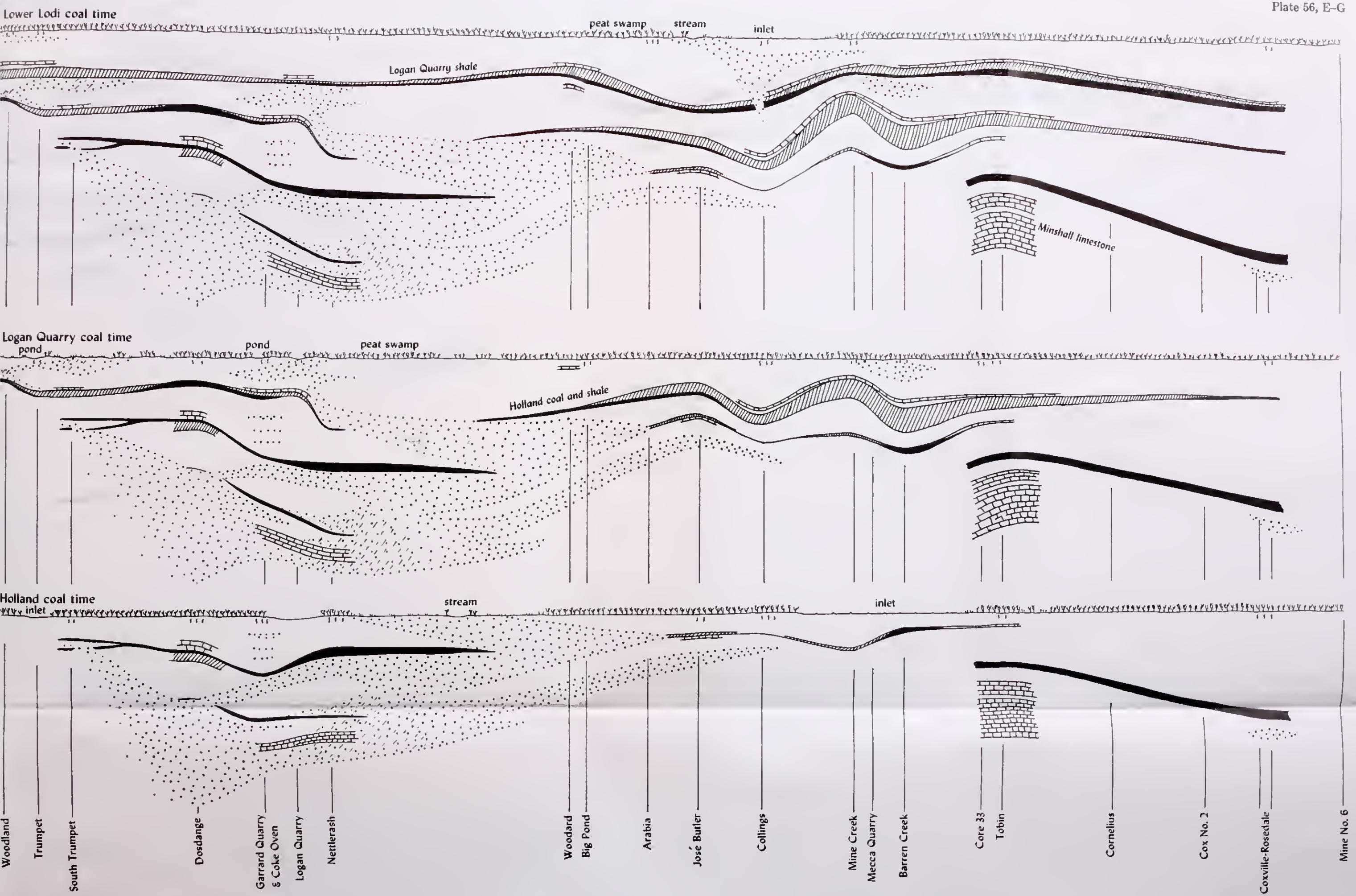
G Lower Lodi coal time


Minshall limestone

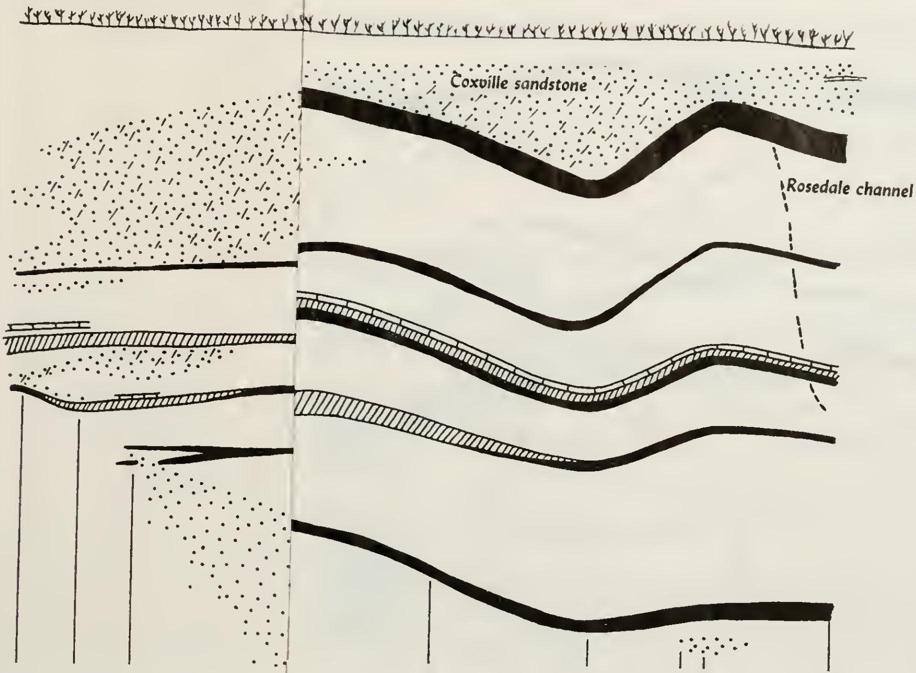
F Logan Quarry coal time

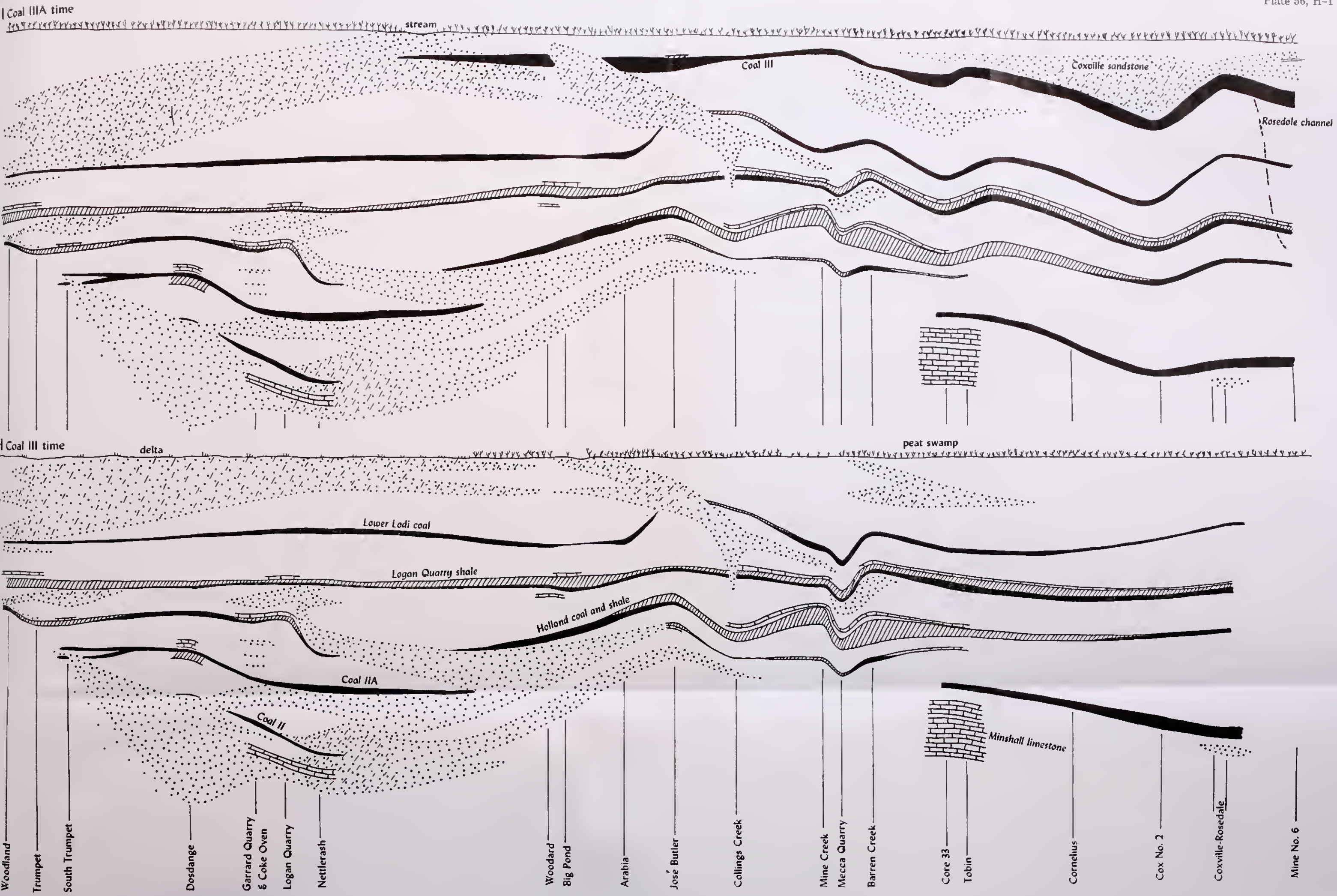


E


Lower Lodi coal time
peat swamp
stream
inlet
Logan Quarry shale
Minshall limestone
Logan Quarry coal time
pond
pond
peat swamp
Holland coal and shale
Holland coal time
inlet
stream
inlet
Woodland
Trumpet
South Trumpet
Dosdange
Garrard Quarry & Coke Oven
Logan Quarry
Nettlerash
Woodard
Big Pond
Arabia
José Butler
Collings
Mine Creek
Mecca Quarry
Barren Creek
Core 33
Tobin
Cornelius
Cox No. 2
Coxville-Rosedale
Mine No. 6

I Coal IIIA time


Coxville sandstone
Rosedale channel


Coal IIIA time
stream
Coal III
Coxville sandstone
Rosedale channel
Coal III time
delta
peat swamp
Lower Lodi coal
Logan Quarry shale
Holland coal and shale
Coal IIA
Coal II
Minshall limestone
Woodland
Trumpet
South Trumpet
Dosdange
Garrard Quarry & Coke Oven
Logan Quarry
Nettlerash
Woodard
Big Pond
Arabia
José Butler
Collings Creek
Mine Creek
Mecca Quarry
Barren Creek
Core 33
Tobin
Cornelius
Cox No. 2
Coxville-Rosedale
Mine No. 6